TRACER GAS REVIEW AND TRACER GAS VENTILATION STUDY OF A TUNNEL BORING MACHINE
PART 1

BY

ONTARIO RESEARCH FOUNDATION

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Tracer Gas Review and Tracer Gas Ventilation Study of a Tunnel Boring Machine

Phase 1: Methodology Selection and Literature Review

for

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1. SOMMAIRE

Les essais en usine d'une perforatrice-excavatrice blindée (PBT) pour le creusement de tunnels, mesurant à l'avant 7,6 m de diamètre, conçue et construite par la firme Lovat Tunnel Equipment Inc., furent menés durant les mois d'avril à juin 1983, dans les bâtiments de cette firme à Rexdale en Ontario. Au terme de ces essais en usine, la Corporation de Développement du Cap Breton (CDCP) prenait livraison de cette machine et prévoyait la mettre en service plus tard cette année.

Au cours des dernières années, les expériences effectuées sur le fonctionnement de machines semblables dans les mines de houille ont montré que l'inflammation du méthane, par suite de frictions, peut survenir au niveau de la partie avant ou tête de perçage de la perforatrice-excavatrice. On attribue la cause principale des explosions antérieures de méthane à une ventilation insuffisante de la partie avant de telle machine, ce qui y occasionnait une accumulation de ce gaz. Voilà les raisons qui ont amené le Centre canadien de technologie minière et énergétique (CCTME), du ministère de l'Énergie, des Mines et des Ressources naturelles (EMRN), à évaluer le système de ventilation de la tête de ces énormes PBT et ce, par le biais d'épreuves en usine utilisant des techniques appropriées de traçage au gaz.

Conformément à ses engagements contractuels, l'Ontario Research Foundation (ORF), un organisme provincial voué à la recherche, entreprit d'abord l'examen des gaz-traceurs disponibles et passa en revue les différentes méthodes techniques employées dans d'autres études; elle sélectionna ensuite les techniques les mieux adaptées pour les utiliser dans l'évaluation dudit système de ventilation, conformément à un protocole établi conjointement par le CCTME, l'ORF et Lovat.

L'étude comporta deux phases lesquelles, en raison d'échéance rapprochées ayant trait à la livraison de la PBT, furent menées simultanément. La phase 1 porta sur l'examen des diverses méthodes techniques et sur la sélection d'une méthodologie; la phase 2 engloba les divers essais sur le système de ventilation de la machine.

Les objectifs, méthodologies, résultats et conclusions détaillés de la phase 1 de cette étude sont inclus au présent rapport.

Objectifs

Le principal objectif de la phase 1 de cette étude consiste en la sélection d'un procédé de traçage au gaz d'utilisation convenable au cours de la phase 2 du programme d'essais du système de ventilation. Ce processus de sélection a comporté l'examen des gaz-traceurs éventuels ainsi que l'examen de systèmes d'analyse et de distribution des traceurs. Au terme de ce processus de sélection, il a fallu élaborer des méthodologies analytiques et d'ajout de ces traceurs.

Toutefois, à cause des échéances rapprochées ayant nécessité l'exécution simultanée des phases 1 et 2, la sélection du traceur a dû être effectuée avant que l'examen n'ait été terminé. Par conséquent, l'examen de la méthodologie a eu comme objectif la validation des méthodes de traçage sélectionnées plutôt que l'étude même du processus de sélection.

Fondement de la sélection des traceurs

La sélection des gaz-traceurs s'est fondée sur l'expérience spécifique de l'ORF sur ces gaz, sur l'examen des caractéristiques du gaz-traceur idéal, ainsi que sur les contraintes imposées par le système de ventilation de la PBT. À noter que la contrainte la plus importante était d'ordre temporel; en raison, effectivement, du changement rapide de l'air au niveau de la tête de perçage de la PBT, on ne disposait que de très peu de temps pour procéder à l'ajout et à l'analyse des traceurs. On a conclu que l'analyse continue offrait certains avantages.

Le méthane et le gaz propane, deux hydrocarbures, furent choisis comme traceurs primaires et les analyses furent exécutées au moyen d'un analyseur-totaliseur d'hydrocarbures (ATH). Ce système fut retenu non seulement en raison de l'extrême rapidité de sa réponse mais aussi pour la précision et la facilité du fonctionnement de l'analyseur-totaliseur d'hydrocarbures. En guise de traceur d'appui ou de remplacement, on opta pour le SF_6 (hexafluorure de soufre) et comme système analytique auxiliaire pour le propane et le SF_6, un analyseur infra-rouge Miran fut sélectionné.

Études en laboratoire

Les études menées en laboratoire précédèrent le programme sur le terrain. La vérification de l'étalonnage des systèmes analytiques furent effectués afin de s'assurer que des temps de réponse convenables puissent être obtenus. Des modifications furent apportées au système d'évacuation Miran dans le but d'en améliorer le temps de réponse.

Une méthode d'analyse continue du SF_6 ayant un temps de réponse rapide fut mise au point d'après diverses méthodologies répérées à la suite d'une recherche préliminaire de la littérature.

Afin de démontrer le type de données prévues durant le programme sur le terrain, on procéda à des simulations en laboratoire d'une technique d'injection de traceur par impulsions. Les résultats obtenus avec ces simulations ont correspondu au modèle de changement du traceur en fonction du temps.

Recherche et examen de la littérature

En quête de références sur les gaz-traceurs et leurs applications dans le cadre d'études sur la ventilation, on effectua une recherche des bases de données portant sur les abrégés chimiques et sur les répertoires d'ingénierie, ainsi qu'auprès du Service national d'information technique, un organisme américain (U.S. National Technical Information Service). L'examen des documents obtenus a convergé pour ce qui est des gaz utilisés, des méthodes analytiques, des applications, des méthodes d'ajout des traceurs et de l'analyse des données.

Selon nos constatations, la sélection d'un gaz-traceur et d'une méthodologie est étroitement liée aux objectifs visés de l'étude. La plupart des études menées sur les traceurs impliquent aussi des études sur la ventilation, notamment dans des bâtiments ou dans le cadre de la dispersion athmosphérique. De concert à une chromatographie et à une spectroscopie à l'infra-rouge aux fins d'analyses, les traceurs les plus fréquemment utilisés sont l'hexafluorure de soufre (SF_6), l'oxyde nitreux (N_2O) et les hydrocarbures.

La plupart des études ont impliqué une décroissance temporelle des concentrations du traceur dans la zone d'essai. Aussi dans la majorité des études, les essais se sont prolongés en terme d'heures et de minutes au lieu de secondes, comme ce fut le cas pour les essais sur la PBT.

Un examen de la littérature a corroboré la sélection des gaz-traceurs et des systèmes analytiques utilisée au cours du programme sur le terrain. Il appert enfin que nul autre système n'aurait mieux convenu à notre étude sur la PBT.

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1. EXECUTIVE SUMMARY

Shop floor testing of a 7.6 m diameter shielded full-face tunnel boring machine (TBM), designed and constructed by Lovat Tunnel Equipment Inc., was conducted during April - June, 1983, at the Company's facilities in Rexdale, Ontario. Following completion of shop floor trials the machine was delivered to the Cape Breton Development Corporation (CBDC) for service later in the year.

In recent years operational experience of such machines in coal mines has shown that frictional ignitions of methane gas may occur in the machine head. Inadequate head ventilation, allowing methane concentrations to build up in the head, is considered to be the major reason for previous explosions. For this reason, therefore, the Canada Centre for Mineral and Energy Technology (CANMET), Department of Energy, Mines and Resources (EMR), decided to assess the head ventilation system of the large TBM during shop floor trials, using appropriate tracer gas techniques.

Ontario Research Foundation (ORF) were contracted to review available tracer gases and methodologies used in other studies, select the most suitable techniques, and use them to assess the head ventilation system according to a protocol to be established by CANMET, ORF and Lovat. The study was divided into two phases, which, because of the time constraints related to delivery of the TBM, were conducted concurrently. Phase 1 included the methodology review and selection and Phase 2 covered the head ventilation test program.

Details of the objectives, methodologies, results and conclusions of Phase I of this study are included in this report.

Objectives

The main objective of Phase 1 of this study was the selection of a suitable tracer gas system for use in the Phase 2 ventilation test program. The selection process was to include a review of potential tracer gases, analysis systems, and tracer delivery systems. Following the selection, necessary analytical and addition methodologies were to be developed.

Because time constraints necessitated that Phases 1 and 2 be carried out concurrently, selection of the tracer had to be made before the review was completed. The objective of the methodology review is, therefore, the validation of the selected tracer methods, rather than the selection itself.

Basis for Tracer Selection

Selection of the tracer gases was based on specific experience of ORF with tracer gases, a review of ideal tracer gas characteristics, and the constraints imposed by the TBM ventilation system. The most important constraint was the fast tracer addition and analysis times required because of the fast air change rate in the TBM head. Continuous analysis was seen to be advantageous.

Hydrocarbon gases, methane and propane, were selected as the primary tracers, using a total hydrocarbon (THC) analyser for analysis. This system was selected because of the very fast response, and the accuracy and ease of operation of the THC analyser. SF_6 was selected as a back-up or alternate tracer. A Miran infrared analyser was selected as an auxilliary analytical system for both propane and SF_6.

Laboratory Studies

Laboratory studies were carried out prior to the field program. Analytical systems were checked and calibrated in order to confirm that adequate response times could be obtained. Modifications were made to the Miran flow system in order to improve the response time.

A method for continuous analysis of SF_6, with a fast response time, was developed, based on methodologies found in a preliminary literature search.

Laboratory simulations of a pulse tracer injection technique were carried out in order to demonstrate the type of data expected during the field program. The results obtained from these simulations were found to fit a model for the change in tracer with time.

Literature Search and Review

Databases covering Chemical Abstracts, Engineering Index, and US National Technical Information Service were searched for references to tracer gases and their applications to ventilation studies. The review of papers obtained focussed on the gases used, analytical methods, applications, tracer addition techniques, and data analysis.

Tracer gas and methodology selection was found to depend greatly on the study objectives. Most tracer studies involved ventilation studies, particularly in buildings and atmospheric dispersion. Sulphur hexafluoride (SF_6), nitrous oxide (N_2O), and hydrocarbons are most commonly used as tracers, with gas chromatography and infrared spectroscopy used for analysis.

Most studies involved the decay with time of a starting concentration of tracer in the test area. Tests were over durations of hours or minutes for most studies, rather than over seconds as required for the TBM tests.

The literature review supported the selection of tracer gases and analytical systems used in the field program. No other systems were found that would have been more suited to the TBM study.

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2. INTRODUCTION

A 7.6 m diameter shielded full-face tunnel boring machine (TBM) has recently been constructed by Lovat Tunnel Equipment Limited at their facilities in Rexdale, Ontario. The machine, following extensive shop floor trials, has now been delivered to Cape Breton Development Corporation (CBDC) for service later this year. Previous experience in coal fields with other similar machines has shown that frictional ignitions of methane gas in the machine head area can and do occur. For this reason the Canada Centre for Mineral and Energy Technology (CANMET), Department of Energy, Mines and Resources (EMR), agreed to assess the head ventilation system of the 7.6 m diameter TBM during shop floor trials of the machine.

Ontario Research Foundation (ORF) was contracted to carry out a study to evaluate the head ventilation system using tracer gas techniques. The study was to be conducted in two phases. Phase 1 would be concerned with the selection of appropriate tracer gas addition, sampling and analytical methods following a literature review of techniques previously employed. In Phase 2 the selected methods would be applied during TBM shop floor trials to evaluate the ventilation system according to an experimental protocol established by CANMET, ORF and Lovat.

Due to the fixed schedule established for all shop floor trials following construction of the TBM and prior to the set delivery date, it was not possible upon receipt of the contract to complete Phase 1 before Phase 2 of the study. The two parts of the project were therefore conducted concurrently and a report on Phase 2 (ORF Report P-4331/G-1) was written and submitted in August, 1983.

Selection of appropriate tracer gas techniques for Phase 2 was largely based, therefore, on the experience and knowledge of ORF staff. This report provides the basis for methodology selections, describes laboratory assessment of selected methods and then gives a summary of findings from the literature search and review. Sections within this latter part of the report cover search methodology; tracers used; addition, sampling and analytical procedures; tracer applications and approaches for data interpretation. Comment is made on the validity and merit of techniques used in Phase 2 of the study based on the findings of the literature review.

3. TRACER GASES AND ANALYTICAL METHODS

3.1 Basis for Selection

In this section the basis for selection of both tracer gases and addition, sampling and analytical methods is presented.

During the past decade ORF has carried out several tracer gas studies using different techniques depending upon the specific application and study objectives. These studies have included the following:

- plume dispersion studies using reduced sulphur compounds to assess dispersion models.
- ventilation studies with sulphur hexafluoride (SF_6) and specific odorants such as methyl salicylate to assess odour complaints within a building.
- ventilation studies within an office complex using carbon dioxide (CO_2) to define indoor air quality.
- a ventilation study using SF_6 to assess the infiltration of external contaminants into coaches of a moving train.

Experience gained during these and other studies, plus information collected from published material, enabled the selection of tracer gas and analytical methods for this study to be selected with some confidence.

3.2 Ideal Tracer Characteristics

An ideal tracer gas should normally meet the following criteria:

- be stable and non-reactive
- be non-flammable
- be non-toxic and non-allergenic
- be inexpensive and readily available
- be detectable at low concentrations
- not be formed from any process operation in the test space
- be absent as a constituent of the test space
- have a density similar to that of air, or the contaminant being modelled.
- be readily analysed, preferably by more than one instrumental technique.

In addition, the preferred analytical technique should be proven, portable, sensitive and not subject to interferences from other gases expected in the test area. Ideally a continuous analyser should be used.

Some of these tracer characteristics are more important than others for specific applications. In this study the very fast ventilation rate placed special constraints on the rapidity of analysis required, thereby also influencing the type of tracers that could be used. This short time scale for each analysis test also lessened the constraints of stability, reactivity, adsorption, and some absorption, since significant effects of this type would not be expected over a short period of time.

The density criteria is probably not very important for this study, again primarily because of the time scale over which ventilation effects occur. Since the objective of the study was to simulate methane leakage, a tracer with a similar density to methane would appear to be appropriate. The density of methane at 25°C and 101 kPa is approximately 0.65 kg/m^3. The density of air, under the same conditions, is approximately 1.19 kg/m^3. Methane is thus lighter than air and will rise. Propane (density 1.80 kg/m^3) and sulphur hexafluoride (5.97 kg/m^3) will both sink in air. The acceleration of a volume of a gas mixture in air can be calculated from the following equation:

where a = the acceleration of a volume of a gas mixture m/sec^2,
p = the difference in density between the gas mixture and air,
p = the density of the gas mixture,
g = the acceleration due to gravity, 9.8 m/sec^2.

Buoyance effects occur on the macroscopic level rather than the microscopic level so the movement of a gas will be dependant on its concentration in a mixture. A volume of air containing 1% methane will have an upwards acceleration of 0.044 m/sec^2 and would rise approximately 0.5 metres in 5 seconds. A volume of air containing 0.1% methane would only rise approximately 5 cm in the same time. Only a very high concentration of gas would move a significant distance in the time required for one air change of the TBM.

For concentrations of any tracers in a range suitable for analysis, buoyancy effects should be insignificant over the short time scale operative in the TBM ventilation system.

3.3 Tracer Gases Selected

In actual practice no tracer gas is able to meet all of the aforementioned criteria. It is considered by the majority of users that sulphur hexafluoride (SF_6) comes closest to being the ideal tracer. SF_6 meets most of the above criteria and current analytical techniques enable it to be detected at sub-parts per billion (ppb) levels. While it has a high molecular weight and is approximately 5 times as dense as air, at the concentrations at which it is normally used in tracer work, it would still take a few hours to sink one metre. Obviously for the present program with tests taking place over a period of a few seconds, the density of SF_6 is not a drawback.

The normal analytical procedure for SF_6 is by gas chromatography using an electron capture detector. This type of analysis is not continuous, however, and approximately 1 minute is required between successive samples. For the purposes of this study that time delay was much too long. The Miran gas analyser is capable of measuring SF_6 continuously down to ppb levels. The response time, however, is barely adequate (10 seconds) as desired for this application.

Other investigators have used various means for converting the electron capture detector to a fast response, continuous detector for SF_6. The key problem to using the electron capture detector in this way is the fact that response by the detector is reduced drastically by oxygen, preventing any detection of SF_6 in an air matrix. Dietz and Cote have overcome this problem in "wave front" chromatography whereby the SF_6 is separated from oxygen in the air using a molecular seive 5A (MS5A) column as in conventional gas chromatography for SF_6(1). However the air sample is allowed to flow continuously through the column for a period of about 30 seconds until oxygen is first detected, instead of using a pulse injection as in the normal gas chromatographic technique. SF_6 is eluted before oxygen on an MS5A column, so effectively 30 seconds of continuous measurement of SF_6 can be obtained from the start of the sample injection until the oxygen interference. Following an analysis in this way requires several minutes to allow a carrier gas to flush the oxygen from the column before another sample can be taken. This technique has been used for measurements of concentrations of SF_6 from aircraft where fast, continuous measurements were required(36).

A second technique for continuous measurement of SF_6 with an electron capture detector, as reported by Simmonds et al, involves the continuous removal of oxygen from the sample stream prior to analysis(37). Hydrogen is added to the sample stream, which passes through a heated precious metal oxidation catalyst, to convert the oxygen to water. The water is then removed in a condenser. This leaves the SF_6 in a matrix consisting essentially of nitrogen plus traces of CO_2 from any organics that were present in the sample. This gas is then suitable for running through the ECD. The technique has been used successfully for tracer work(37).

This latter option seemed to be the most promising approach to continuous SF_6 measurement for this study and, since it was considered practical to assemble such a system in time for the field program, SF_6 was chosen as one of the tracers to be used. The Miran gas analyser and portable gas chromatograph could also provide backup analytical capability for SF_6.

An obvious candidate for a tracer gas was methane itself, even though it is a potentially explosive gas when present at concentrations of 5% to 15% in air. It is generally present in ambient air at a concentration of only 1 or 2 parts per million (ppm) and is readily detectable by more than one instrumental technique. Usually this gas is analysed by gas chromatography with flame ionization detection. Continuous analysis with a total hydrocarbon analyser (a flame ionization detector with a continuous sample flow) is also practical, provided that there are no significant interferences from other hydrocarbons. Analysis by infrared techniques, such as with the MIRAN gas analyser is also feasible. These methods all allow detection at the ppm level.

Other hydrocarbons can potentially be used as well. There is an advantage in using a higher hydrocarbon, with detection using a THC analyser, since an increased response is obtained for the same volume of tracer injected. Response is roughly proportional to the number of carbon atoms in the hydrocarbon molecules, so propane has approximately three times the response compared to methane. Propane, being the highest gaseous hydrocarbon, was considered a good tracer gas for this study. Methane was chosen as well, primarily to confirm results obtained with propane and so ensure that there were no significant effects due to density.

3.4 Tracer Addition Technique

The selection of a tracer addition technique also depends on the system to be studied. Tracer addition can be continuous, with measurement of the increase and decrease of tracer with time, as the tracer is introduced and shut off. Alternatively, a pulse injection of a known quantity of gas can be used. For the purposes of this study, with the rapid ventilation rate and the need to collect as much data as possible in a short period of time, the pulse technique was chosen for the major portion of the study. The pulse technique involves a minimal addition time and the ventilated volume is soon cleared of tracer to allow another test.

A very rapid method of injecting a tracer pulse was required. The preferred time for pulse injection was 1 second or less. A small 150 mL stainless steel sample bomb was found to be capable of releasing its contents in about 1 second when pressurized to 205 kPa (gauge). A solenoid valve at the outlet of the bomb allowed quick release of the contents and also enabled remote operation. Because the amount of tracer required for an effective trace was not known, three sizes of sample bombs (150 mL, 500 mL and 1500 mL) were prepared. Obviously the smaller sample bomb could release its contents more quickly than the others and was preferable as long as the amount of tracer released was adequate. Additional flexibility of this system could be obtained by adjusting the pressure of the bomb.

4. LABORATORY DEVELOPMENT AND EVALUATION OF ANALYTICAL AND ADDITION METHODOLOGIES

Laboratory studies were carried out in order to assess the procedures planned for use in the field program. These included performance tests and calibrations for the total hydrocarbon analyser and Miran gas analyser. A continuous electron capture detection system for measuring SF_6 was developed and tested. Tracer addition apparatus was constructed and the methodology for their use was tested by laboratory simulation of the pulse injection technique.

4.1 Analytical Systems Performance and Calibrations

The measurement of tracer concentrations from a pulse injection into the rapidly ventilated head of the TBM requires an analytical system with a very fast response time. Response times for the THC analyser and Miran analyser were therefore determined and optimized.

The response time of the Ratfisch Model RS5 total hydrocarbon analyser is very short. The rise time to 90% of the final value was found to be 2 seconds (Figure 1). With the short sample line (approximately 1.5 m) used for testing the response time, a lag time of 2 seconds was observed. Longer sample lines increased the lag time but did not appreciably effect the rise time.

The response time of the Miran gas analyser is primarily limited by the sample flowrate through the large 5.5 L cell volume. With the sample pump supplied with the instrument operating at its maximum 15 litres per minute, three cell changes per minute will occur, resulting in a rise time to 90% of about 45 seconds. In order to improve this, other pumps were tried with this instrument. An upper limit to the flow occurs, however, due to a significant pressure drop across the cell occurring at high flows. The resulting pressure change in the cell causes a change in the instrument calibration. A rise time to 90% of approximately 13 seconds was the optimum obtained. The lag time was found to be about 1 second, using a sample line approximately 3 m long.

A calibration curve for SF_6 from 25 ppb to 9 ppm was obtained for the Miran gas analyser by injection of known quantities of a 1% SF_6 in air mixture into the gas cell. The lower concentrations were obtained by first diluting the 1% SF_6 with known quantities of air in Tedlar (polyvinyl fluoride) gas bags.

An AID (Analytical Instruments Development) portable gas chromatograph equipped with an electron capture detector was calibrated for SF_6. This analyser could then be used as a supplementary SF_6 measurement system for use as required in the shop floor trials. Calibrations were obtained by serial dilution of 1% SF_6 in air in Tedlar gas bags. Response was found to be linear over the range of concentration used, from 0.3 ppb to 3 ppb.

4.2 Development of Continuous ECD System

Since SF_6 was desired for use as a tracer and the Miran analyser is relatively slow, some alternate means of rapid continuous detection was desired. It was decided, therefore, to adapt an electron capture detector for continuous measurement of SF_6, following the method used by Simmonds et al(37).

The key element in the continuous ECD system is the catalyst used for removal of oxygen by the oxidation of hydrogen. Simmonds et al used a palladium-gold (6:4) alloy tube, 10 cm long x 0.3 cm diameter, packed loosely with 20% palladium on asbestos fibre. Because of time constraints, it was not possible to obtain this type of catalyst. Oxidation catalysts on hand were therefore examined instead. This was accomplished by packing a 7.5 cm x 0.3 cm O.D. stainless steel tube with the catalyst to be tested and wrapping it in a fibreglass heat tape, controlled by a variable AC transformer. An air flow of approximately 100 cc/min was passed through the tube and hydrogen was metered through a needle valve and mixed with the air at the tube inlet. The outlet gas stream from the catalyst tube passed through a condenser and a silica gel trap, then entered an oxygen analyser (Taylor Servonex, Model PA272). The temperature of the catalyst was monitored using a thermocouple. The lowest temperature required for oxidation could be determined by a sudden increase in the catlyst temperature and a drop in the oxygen concentration at the outlet.

Silver powder was found to be an effective catalyst, allowing complete removal of oxygen at 200°C. However, the mesh size used, 60/325, was too small and an undesirably high back pressure was created as the tube heated up. A platinum on alumina catalyst, Girdler G-43, 8/14 mesh, was also effective at 200°, without causing a significant back pressure. This catalyst was, therefore, used in the further development of the system.

The platinum on alumina catalyst, hydrogen addition system and heating system were then connected to the ECD in a Varian 1400 gas chromatograph. A sample delivery system, consisting of a stainless steel bellows pump (Metal Bellows Model MB-41), back pressure regulator, pressure gauge, and needle valve, allowed delivery of a precisely controlled flow of sample through the catalyst. Matheson zero grade hydrogen was used. A small condenser consisting of a 0.3 cm O.D. tube within a 0.6 cm O.D. tube was installed after the catalyst, in an ice bath, for water removal. The dried gas stream from the condenser then entered the ECD.

Tubing connections were made using 0.15 cm O.D. stainless steel tubing wherever possible in order to minimize the volume of the system and so reduce the response time.

The response of the ECD was examined using this system. It was found that the hydrogen flowrate was critical to the background signal obtained. Insufficient hydrogen resulted in residual oxygen in the sample and, therefore, a drastically reduced standing current. Too much hydrogen also resulted in a reduced standing current, but not to the same extent as with excess air. The optimum hydrogen addition rate could be readily determined by adjustment of the hydrogen metering valve to obtain the maximum standing current.

The temperature of the condenser system also had a significant effect on standing current, due apparently to residual water vapour in the gas stream. A second condenser was added, with cooling to -15°C by means of a salt and ice bath. A thermoelectric cooler was used to maintain the first condenser at 3°C to minimize the load on the second condenser and prevent blocking of the second condenser with ice. This cooling system improved the standing current considerably, to a maximum of approximately 3.5×10^{-9} amps standing current. This standing current is still less than that obtained in normal gas chromatographic use of the detector, but is adequate for use over a limited concentration range. The final configuration of the continuous ECD system is depicted in Figure 2.

The response of the ECD to SF_6 was then determined. A calibration curve was obtained over the range of 1 to 6 ppb, using standards prepared by serial dilution of 1% SF_6 in air. At 4 ppb response began to get non-linear. An estimated minimum detectable concentration for the system was 0.1 ppb, based on a response of two times the noise level.

4.3 Simulation of Pulse Injection Technique

In order to evaluate the type of data expected from a pulse injection technique, a laboratory simulation was conducted using a plexiglass drum, 75 cm high and 39 cm ID with approximately 90 litres volume, into which a known amount of propane could be injected. A total hydrocarbon analyser was used to measure the propane concentration in the drum. Air was injected into the drum at a known flowrate, enabling the calculation of the air change rate for the system. Small quantities of propane were injected through a septum into the drum and the analyser response was recorded using a chart recorder.

Attempts were made to simulate the effect of injection of tracer into a poorly ventilated zone. Injections of propane were made into a plastic beaker fixed just under the septum on the inside of the drum. This had no appreciable effect on the trace observed. In order to create a more definite stagnant zone, a different method was used. A 500 mL gas samle bottle was filled with a known concentration of propane. The contents of this bottle were pumped out by a miniature sample pump at a known flowrate. The bottle and pump were placed within the drum and the hydrocarbon concentrations were recorded. This procedure created an artificial stagnant zone, the gas bottle, with a known air change rate, emptying into a larger volume with a faster air change rate, which was also known. Figure 3 shows the trace obtained for this and the other simulation tests.

No set method of evaluating tracer pulse injections had been found in the literature at this point. However, Kissell and Bielicki give an equation based on theoretical considerations which can be used with decay of tracer from a constant concentration(12):

where $y(t)$ = the concentration (or alternatively the quantity) at time t in the whole chamber,
K_y = rate constant for the whole chamber,
K_x = rate constant for the stagnant zone,
t = time,
y_0 = initial concentration in the chamber,
x_0 = initial concentration in the stagnant zone.

For the case where a tracer is injected into a stagnant zone, with no tracer in the rest of the chamber at the start, the last term of this equation is eliminated, since $y_0 = 0$.

From the laboratory simulation, all the variables in the above equation, x_0, K_x and K_y can be determined and so $y(t)$ can be calculated. The experimental results agreed closely with that predicted, within the accuracies of the flowrates and concentrations involved.

5. LITERATURE SEARCH AND REVIEW

At ORF computer terminals currently permit access to eight major information retrieval systems. These eight systems permit searching of over 150 databases for technical literature. To obtain relevant information on tracer gases three specific databases, listed below, were searched:

CAC	Bibliographic information appearing in Chemical Abstracts from 1977 - 1983;
COMPENDEX	Bibliographic information appearing in Engineering Index from 1970 - 1983;
NTIS	A listing of U.S. government-sponsored research, development and engineering prepared by federal agencies, their contractors or grantees, from 1964 - 1983.

Key words selected for these searches were TRACER, GASES, VENTILATION, AIR, LEAKAGE and INFILTRATION. A total of approximately 200 references were printed out in response to these keywords and after reviewing some abstracts, copies of selected reports, papers and articles were ordered. Additional material pertaining to the subject area contained in the ORF library and staff files was also reviewed.

A complete listing of all references obtained is given as Appendix A to this report. Specific publications reviewed are referenced in the following sections of the report and listed with abstracts in the final section. The following review considers the type of tracer gases previously used and their applications, methodologies for addition, sampling and detection of tracers and data analysis.

5.1 Tracer Gases and Applications

A summary of the literature review of tracer gases, uses and methodologies is given as Table 1 under a series of headings, which are used for the following discussion.

5.1.1 Applications

The most frequent application of tracer gases in recent years has been to evaluate ventilation systems in buildings and homes(4,5,7,9,16), in industrial plants(10) and in underground mines(6,19,24). In most cases studies have been made because of concerns of adverse health effects from exposure to concentrations of various contaminants. These contaminant concentrations may be higher than they should be in plants or mines due to a lack of process control or inadequate ventilation. Recent efforts to conserve energy by increasing insulation and/or reducing air leakage and ventilation requirements has sometimes caused a deterioration of indoor air quality in offices and homes to the detriment of occupant health. Studies have been made, therefore, using tracer gases to determine air exchange rates(5,7), air infiltration and leakage(16), and to assess ventilation efficiency(28,29).

In mines studies have been conducted to assess overall and local ventilation(20) and to determine leakage through mines stoppings(11,18). Specific studies have been made to assess ventilation in relation to equipment such as fans, hoods and dust control devices.

Tracer gases have also been used to determine atmospheric dispersion of pollutants released from sources into the ambient air(2,8). Such studies have usually been carried out to validate proposed dispersion models(33), or to determine the effects on dispersion of parameters(14) such as meteorological conditions, building and stack heights, release points and release rates.

A few studies have utilized tracer gases to evaluate phenomena such as dispersion in large gas lines(3), mechanisms in fluidized bed reactors(31) and adsorption equilibria(32).

5.1.2 Tracers Used

For studies in air it is apparent that, currently, sulphur hexafluoride, SF_6, is favoured as a tracer gas. This is particularly true for studies conducted in North America, whereas in Europe nitrous oxide, N_2O, is often preferred. As mentioned in Section 3, SF_6 has more characteristics of an 'ideal' tracer gas than other tracers previously used. Since it can be accurately detected at a concentration an order of magnitude lower than those for other tracer gases, small volumes of the gas are required for test programs. However, some researchers consider that the high density of SF_6 and the extreme care required for analysis at low levels are major disadvantages which preclude use of the gas in some applications.

An intercomparison of tracer gases used for air infiltration measurements(4), which included a review of other similar studies, showed that air exchange rates determined using SF_6 as a tracer were slightly higher (10%) than those determined when using either N_2O or CH_4 as tracers. The differences could not be explained on the basis of molecular diffusion or stratification and it is considered that, though such differences are real, they are small enough to fall within the uncertainty associated with a single measurement(5). Such differences might be explained by absorption or adsorption effects because of the extremely low concentrations being measured, or they may result from the different analytical systems used for the various tracers. Problems related to analytical systems for tracer gas measurement are discussed later in the report and specific difficulties pertaining to continuous monitoring of SF_6 were presented in Section 3.

Nitrous oxide, N_2O, is a common anesthetic and has many of the properties of an ideal tracer gas. It is relatively stable, not present to any degree as a background constituent of air, and is readily detected on a continuous basis at concentrations of less than one part per million. However, it is soluble in water and may contribute to adverse health effects in people exposed to levels commonly employed in tracer gas studies(25). A number of properties for N_2O, SF_6 and other tracer gases are given in Table 2.

Methane, CH_4, is a contaminant of concern, particularly in underground mining where explosions can and do occur as a result of methane leakage at the working face. It is also a useful tracer gas since it can be continually monitored by more than one instrumental technique at low ppm concentrations, is readily available and is not normally present in ambient air at levels above a few ppm. It is considerably lighter than air, but as previously mentioned, stratification is not considered to be a problem in most applications. Provided that CH_4 concentrations do not approach the lower explosion limit of 5% in air and no other hydrocarbon gases are present, it is a useful tracer(4,30). In order to minimize the volume of tracer used in a given test, both ethane, C_2H_6, and propane, C_3H_8, have been used as tracer gases(25). These hydrocarbons have similar properties to methane but have higher densities. Since the response of the preferred analytical detector is essentially proportional to the number of carbon atoms in the hydrocarbon molecule for equivalent gas volumes, approximately one third of the volume of tracer gas is required when using propane instead of methane. This allows a greater range of concentrations to be used well below the lower explosion limits for these gases.

Most other tracer gases listed in Table 2 have one or more significant disadvantages for use as tracers, particularly for studies such as that of the TBM head ventilation system where specific requirements had to be met. Carbon dioxide, CO_2, is relatively inert and detectable by available analysers at concentrations down to a few ppm. It is, however, present in air at levels of 300 ppm and higher, greatly restricting the useful concentration range, and is very soluble in water. It has been used successfully in specific applications where these characteristics were not a problem(10,31).

Some earlier studies(4) of air infiltration in buildings use hydrogen, H_2, as a tracer gas. Since this gas is extremely reactive in the presence of oxygen and heat or flame, is an extremely light gas and is not readily detected at low concentrations, it is not a useful tracer gas. Radioactive tracers, such as ^{43}Ar, ^{85}Kr, ^{133}Xe and C-14 tagged CO, ethane and ethylene, have also been used for both ventilation(10) and other(32) studies. Such tracers are not readily available, are expensive to use in large quantities and are not accurately detectable at low concentrations.

Specific fluorocarbons such as $CBrF_3$ and CBr_2F_2 have been used for dispersion studies(2,8). These compounds have similar properties to SF_6 and are detectable at very low levels in air. Continuous monitoring of these tracers is, however, difficult and considerably limits their application. Additional compounds which have been used as tracer gases(33,34) are not suitable for ventilation studies where in-situ continuous monitoring and quantitative measurements are required.

5.2 Test Methods and Duration

There are three basic methods of using a tracer gas to assess air flows within a test space. These are listed in Table 5.1 as 'pulse', 'decay' and 'constant source' methods.

In the 'pulse' method a known volume of tracer gas is injected into the test space as rapidly as possible and the time noted. At one or more sampling points the concentration of tracer gas is monitored over a time interval. This interval is normally one that allows the tracer gas concentration to increase to a maximum value and then decay to zero or some background level.

The concentration 'decay' method requires addition of sufficient tracer gas into the test space of interest to attain a homogeneous concentration. Addition of gas is then stopped and the decay of the gas concentration over time is then monitored.

For the 'constant source' or 'continuous flow' method tracer gas at a known fixed rate is continuously metered into the test space. At one or more sampling points the change in tracer gas concentration with time is followed.

Assuming that all other test conditions are the same and remain constant over the test period, the data obtained from the latter two methods are essentially identical. Thus, the decay curve in the concentration 'decay' method is equal but opposite to the curve obtained in the 'constant source' method, where the tracer gas concentration gradually increases with time to a maximum value. The 'pulse' method can be considered as a modification of the 'decay' method.

These methods have advantages and disadvantages depending upon the type of application, objectives of the test and the variation of parameters which may affect the tracer gas concentration curve. For the 'decay' method it is often difficult to attain a homogeneous concentration initially. The 'constant source' method may require use of considerable quantities of tracer gas if the time interval required for measurement is extensive. The 'pulse' method requires addition of tracer gas in a very short time interval compared to the period over which gas concentrations will be measured. All three methods have been used with success in air infiltration or ventilation studies with the 'decay' method slightly favoured, based on the data contained in Table 5.1.

More detailed information on these methods and their modifications is contained in published articles (5,7,25) dealing with automated air infiltration measurement systems.

The test duration frequently has some impact on selection of the methods and tracer techniques to be used. For most ventilation and dispersion studies the time period over which tracer gas concentrations are measured is usually in the range of 30 minutes to several hours. Within this time frame most tracer gas methods and techniques are applicable depending on the test objectives. Some infiltration measurements in homes have been taken over several days (35) and a specific mine study of leakage rates required monitoring of tracer gas concentrations for more than a month. In the former study a 'constant source' method was used and in the latter study a 'pulse' method was found to be most appropriate.

More constraints are placed on the selection of suitable methods and techniques when the test period is very short, taking place over a few minutes or even seconds. Two studies have been completed in evaluating mine face ventilation systems, when operating mine equipment underground, in which measurements were required over a 1 - 3 minute period after tracer gas addition (1,22). 'Pulse' methods were used in both cases.

5.3 Tracer Gas Techniques

Various techniques have been used to add, sample and analyze the tracer gas in previous studies. The specific application, study objectives, properties of the tracer to be used and many other parameters may influence the choice of techniques, as illustrated below.

5.3.1 Addition Techniques

Table 5.1 indicates that tracer gases have been added to the test space or region of interest from cylinders(2,3,10), lecture bottles(6,17), syringes(1,5,16), permeation tubes(35) and spray systems(34). If the 'constant source' method is used, then for most tracer gases considerable quantities of gas are required. Addition from a cylinder under pressure is therefore an appropriate technique with the rate of addition controlled by valves and monitored by rotameter or critical orifice. The major difficulty with this approach is to maintain accurately, over an extensive time period, a fixed known addition rate of the tracer.

When SF_6 or perhaps some other fluorocarbon is selected as the tracer gas, large gas volumes are not required since the gas can be detected at extremely low concentratins (sub-ppb). Though this solves any problem relating to required gas quantity the very low release rate introduces additional problems. Metering the gas at a fixed low rate becomes more difficult and any small leakage or other loss of the tracer gas introduces large errors in any calculations made pertaining to gas detection.

Permeation tubes for specific gases(35) eliminate the need for bulky addition equipment at the test site. However, the release rate of the gas is usually very temperature dependent and maintaining a constant rate of flow of gas can be difficult. Also, few suitable tracer gases lend themselves to this technique.

An increasing interest in air infiltration studies in buildings has caused the development of automated systems(7,13,25,26) for adding, sampling and measuring tracer gases. Tracer addition is usually from a cylinder or lecture bottle activated by timer and solenoid valves with the entire system controlled by programmable calculator, microprocessor or microcomputer. Such systems are expensive to produce, but not to operate, and bring accuracy, reproducability and flexibility to tracer gas studies of this type.

For the most commonly used 'decay' method the quantity of tracer used is not important. Thus tracers have been released for short time periods directly from pressurized containers, syringes, bags or from spray systems. In this method it is important to achieve a known homogeneous initial tracer gas concentration. This has been accomplished by physically moving the source around the test area, adding gas at more than one location, and using fans or mechanical means to mix the tracer gas. Problems encountered with the 'decay' method have frequently resulted from a lack of assurance that the initial gas concentration was accurately known.

The 'pulse' method requires tracer gas to be added as rapidly as possible at the injection point or points into the test space. Accurately knowing the volume of gas added may be required, though for a comparative assessment of gas concentration curves, to determine parametric effects, the actual volume of tracer added is not needed, provided the same volume is always added. Gas injected from a syringe or directly from a cylinder has generally been favoured in previous ventilation studies. Manual operation of a syringe is unlikely to give reproducible results, particularly for rapid injection. An automated system which allows a known volume of gas to be added from a pressurized vessel in less than one second is perhaps the optimum technique currently available.

5.3.2 Sampling Techniques

Techniques used for collecting a sample of air containing tracer gas after addition of the tracer greatly depend upon the analysis to be performed. For direct on-site analysis the air sample is usually withdrawn, from a duct or test space, through tubing, by a pump, to the analytical system. Sufficient gas flowrate to provide an adequate sample volume for analysis is required and all sampling lines should be as short as possible and be of a material and size that does not contaminate the sample to be analysed or allow adsorption of tracer to occur. An ideal situation is realized in specific dispersion studies where the analyser is located within the test space (ie. ambient air), and hence samples are taken simply by actuating a valve on the instrument.

In cases where samples have been collected and transported to the analytical system at some other location, either immediately after sampling or at a later time, a variety of devices have been used. These have included syringes(1,6,8,12), sample bottles and containers(17,19,22), sample bags(3,4,5), impingers(4,33) and adsorbents(2,35). Samples are usually drawn into these devices at a measured rate via tubing by a pump. For such sampling techniques where air samples are collected into some type of container, air leakage into, or sample leakage out of, the container is possible and adsorption of tracer on surfaces can occur. If the sample is not analysed immediately after collection, then these effects may introduce large errors in tracer gas concentrations measured. Also, for all such samples, the tracer concentration is an average value for the time period over which the sample was collected.

If the air sample is passed through a chemical solution for absorption and/or reaction of the tracer gas, or through a solid adsorbent for collection, then collection and/or removal efficiency must be known in order to determine the true tracer gas concentration.

It is apparent that automated techniques which effect sampling directly to an analyser for in-situ analysis minimize the likelihood of sampling errors, and are preferred for all tracer gas methods.

5.3.3. Analytical Techniques

Apart from one or two projects with specific tracers that required wet chemical analysis(4,33), most tracer gas studies have employed instrumental techniques for direct analysis of samples. Details of instrument function, calibration and conditions for use are given in several of the referenced publications listed in the final section of this report.

An ideal analyser is one which is inexpensive, easy to use, specific to the tracer of interest, sensitive, has a linear response over a wide concentration range, gives a fast response upon initial detection, provides accurate and reproducible data and can act in a continuous mode. Unfortunately, no analyser has all of these desired characteristics.

Analysis of SF_6 is generally made using a gas chromatograph with electron capture detection (CG-ECD). As previously stated, this technique is extremely sensitive to SF_6 and other highly halogenated compounds. Oxygen is a specific interferant in the analysis of low concentrations of SF_6 because it is present in air samples at such a high concentration and is sensed by the detector. Several chromatographic columns have been recommended for separation of SF_6 and O_2 peaks and analysis of SF_6 by this technique is routinely carried out down to sub-ppb levels. To continuously measure SF_6 by this technique, however, requires considerable modifications to the analytical system. This has been discussed earlier in Section 3.

SF_6 may also be analysed directly by infrared (I.R.) spectroscopy. This technique is applicable to numerous gases, operating the instrument at different wavelengths. It is the preferred technique for N_2O and CO_2 and has also been used for CH_4 and other hydrocarbons. The major disadvantages of I.R. instruments are the fairly slow response of the analysers and the potential for interference at specific wavelengths by other compounds which may be present in the air.

For CH_4 and other gaseous hydrocarbons, a preferred technique is gas chromatography with flame ionization detection (GC-FID). Continuous hydrocarbon analysers using flame ionization detection are available to give a total concentration of all hydrocarbons in sampled gas. These instruments are sensitive, accurate and have a fast response time. The major problem with respect to analysis of a specific tracer such as methane or propane would be errors in measurement caused by the presence of any other hydrocarbon in the sampled gas. An additional disadvantage for most gas chromatographic techniques is the need for ancilliary bulky equipment such as gas cylinders to provide carrier gas flow and, for FID detectors, hydrogen and air for the flame. For all instruments monitoring tracer gas concentrations on a continuous basis, it is essential to perform zero and span gas calibration checks at regular intervals.

5.4 Data Analysis

Several publications(13,26,28) have reviewed the theoretical basis for tracer gas methods discussed previously, assuming that the tracer gas is well mixed after addition, and that the tracer concentration decays smoothly in exponential fashion with time. More complex equations have been formulated(29,36) to account for observed tracer gas concentration versus time curves, in building air filtration studies, to account for varying air flow in different rooms, and from room to room. Equations have also been developed(9) to account for non-perfect mixing of the tracer.

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Consideration has also been given to theoretically account for the presence of eddy or stagnant air zones within the ventilated space of concern(12).

Once the tracer gas concentration versus time curves have been obtained, the most common analytical approach has been to plot the log of the concentration against time to obtain a straight line. The negative slope of this line is proportional to the air exchange rate within the system. In many cases a simple straight line is not observed. Sometimes two straight lines with different slopes give the best fit to the data and sometimes a straight line cannot be drawn at all. These anomalies are considered to result from poor mixing and even non-mixing of the tracer gas.

In order to assess the efficiency of the ventilation system a useful approach is to plot the percentage of tracer gas removed at a given time against time. This simple analysis is particularly informative when assessing effects of different conditions and can be carried out regardless of the slope of the tracer concentrations - time curve. Studies made of ventilation systems in which several parameters may affect the air flow give complex tracer concentration - time curves which are not readily analysed. Computer techniques may be the only means of interpreting such data.

5.5 Comments

The search and review conducted of published data from previous tracer gas studies indicated the following:

- Selection of tracer gas(es), methods of application and techniques for adding, sampling and analysing the gas depend upon the type of study to be made and the study objectives.

- Most tracer gas applications are to the study of ventilation systems, air infiltration or atmospheric dispersion.

- Sulphur hexafluoride (SF_6), nitrous oxide (N_2O) and hydrocarbons such as methane (CH_4), ethane (C_2H_6) and propane (C_3H_8) are the most common gases used as tracers.

- Of the three main methods of tracer application, 'pulse', 'decay' and 'constant source', the 'decay' method is most frequently used.

- Most tracer gas studies involve test measurements over minutes and hours. Very short tests lasting less than one minute are unusual and limit the number of techniques that can be used.

- Tracer gas addition techniques are varied, with automated release from a pressurized vessel being the most reliable and accurate.

- Syringes, bottles and bags have been used to collect air samples for subsequent analysis. If possible direct sampling of the air into an on-site analyser is the preferred technique to provide a representative sample and minimize loss of the tracer gas.

- Instrumental techniques are usually used for tracer gas analysis, with gas chromatography (GC) and infrared (I.R.) spectroscopy most common. I.R. analysers and GC's with flame ionization detectors (F.I.D.), with recorders, allow continuous real-time analysis to be made, providing optimum data for analysis.

- Plots of the logarithms of the tracer gas concentrations versus time and percentage of tracer gas removed against time can give useful information about air exchange rates and ventilation effeciency. In studies where several parameters affect the shape of the tracer gas concentration versus time curve, theoretical interpretation of the data may be difficult and require the use of computer techniques.

The findings of this review support the selection of tracer gas methods and techniques made for the shop floor tests of the TBM head ventilation system, reported as Phase 2 of this study. Two of the three most commonly used tracer gases were chosen with a preferred automated addition technique and direct sampling to the two most appropriate analytical systems giving continuous real-time concentration measurements.

6. REFERENCES AND ABSTRACTS

1. Divers, E., Jayaraman, N., and Custer, J., "Evaluation of a Combined Face Ventilation System used with a Remotely Operated Mining Machine", U.S. Bureau of Mines Information Circular 8899, 1982.

> This Bureau of Mines report presents results of an underground evaluation to determine the respirable dust and gas control effectiveness of a combined (push-pull) face ventilation system for coal mines. The system utilizes both blowing and exhaust curtain, continuous miners equipped with radio remote control, and flight conveyors. Bureau of Mines tests showed a 97% reduction in respirable dust concentrations from the usual cab position on the continuous miner to the remote control operator's position. This allowed the remote control operator to be

well within, and the usual cab position to exceed, Federal respirable dust standards. Tests utilizing a safe tracer gas, sulfur hexafluoride (SF_6), to determine the face ventilation effectiveness of the combined blowing and exhaust system showed that the system also has excellent methane dispersion capability.

Where wide entries permit, this combined face ventilation system and use of remote control can be a very effective method for dust and gas control.

2. Elias, L., McCooeye, M., and Gardner, G., "On-site Measurement of Atmospheric Tracer Gases", Geophysical. Res. Letters, Vol. 3, No. 1: Pages 17 - 20, 1976.

In-situ GC analysis of SF_6 and halofluorocarbons in the atmosphere was achieved by sampling a measured volume of ambient air through a short adsorption tube, or precolumn, from which the collected vapours were released by heating and then transferred directly by the carrier stream to the analytical column. The collection, transfer and analysis operations were performed in the one instrument with the aid of gas sampling valves, thereby minimizing the risk of loss or contamination associated with other sample storage and removal procedures. Field trials using CBr_2F_2 and SF_6 as tracers have demonstrated the efficacy of the technique for the quantitative measurement of such gases in the atmosphere. The detection limit attained in this work is estimated to be about 5×10^{-14} v/v.

3. Fediw, T.J., Nemeth, E.J., and Caram, H.S., "Tracer Study to Measure Deposits and Dispersion Coefficients in Large Diameter Gas Lines", Chem. Eng. Sci., Vol. 36, No. 9, Pages 1575 - 1577, 1981.

A gas tracer was used to determine dispersion coefficients and deposit accumulation in two 12-mile long coke-oven gas pipelines.

Sulfur hexafluoride (SF_6) was used as the main tracer since it could be detected in the parts per billion concentration range using a gas chromatograph equipped with an electron capture detector. Using a small tank filled with SF_6 to 30 psig, a slug of tracer could be introduced into the lower pressure (8-12 psig) pipeline in less than a second. The short injection time justified the approximation of instantaneous injection used in the model.

At the downstream sampling point, a manifold of gas sampling bags was connected to the pipeline. Quick-action ball valves on the manifold allowed each sample to be collected in one second. Results of the experiments are presented.

4. Grimsrud, D.T., et al., "An Intercomparison of Tracer Gases used for Air Infiltration Measurements", ASHRAE Transactions 86(1), Pages 258-267, 1980.

A direct intercomparison has been made between common tracer gases used to measure air infiltration rates in buildings. The results indicate that air exchange rates measured using sulfur hexafluoride, SF_6, are slightly larger than those measured using methane, CH_4, or nitrous oxide, N_2O. The ratio of air change rates measured using SF_6 to air change rates measured concurrently using a lighter tracer gas was found to be 1.10 ± 0.10.

5. Grot, R.A., Burch, D.M., and Silberstein, S., "Measurement Methods for Evaluation of Thermal Integrity of Building Envelopes", U.S. Department of Commerce NBSIR, 82-2605, 1982.

This report presents various measurement and inspection techniques for assessing the thermal performance of the exterior envelopes of buildings. The inspection techniques include the use of ground-based infrared thermographic surveys, aerial infrared surveys, tracer gas air infiltration measurements, pressurization tests for measuring the tightness of the building envelope, and spot radiometer surveys for detecting gross defects. Heat flow meters, a portable calorimeter, and a microprocessor-driven envelope testing unit are also considered. For each technique, recommended procedures are provided; they include equipment requirements, conditions under which the techniques can be carried out, calibration, accuracy, and limitations.

6. Hall, C.J., "Field Testing Tracer Gas Survey Techniques to Quantify Leakage Ventilation", U.S. Bureau of Mines CFR 12-76, 1975.

Twenty eight pulse release sulfur hexafluoride tracer gas field tests were run in a multi-level multi-vein hard rock mine to measure leakage ventilation. The mine had numerous underground booster fans and gob filled old stopping areas and consequently numerous leakage paths. The tests proved that the equipment and methods developed by the USBM can be used successfully in complicated ventilation circuits. The leakage quantities varied each time a major change was made in the main ventilation circuit. Usually leakage quantities had to be remeasured after a main ventilation change, but measurements could be duplicated for any one configuration except under certain defined circumstances. The characteristics of an individual leakage path could be determined from the difference between the measured sum of two paths and the calculated characteristics of one of the paths. Many leakage paths could not be evaluated accurately on one shift. Comments are made on equipment performance and field techniques. Programs for the calculation of gas concentrations and recirculation from measured data and for the mechanical integration necessary for a calculated leakage characteristic have been written for an HP 9810 and are included.

7. Harrje, D.T., and Grot, R.A., "Automated Air Infiltration Measurements and Implications for Energy Conservation", Proc. of the Int. Conf. on Energy Use Manage., Oct. 24-28, 1977, Pages 457-464, 1977.

In the average home approximately one third of the energy for space heating is lost through air infiltration. The driving forces for air infiltration often become more severe in larger buildings. Correlation of air infiltration with parameters that are building-related (cracks, seals, porosity, etc.), occupant-related (door, vent, window openings, etc.), weather-related (wind direction, and intensity, outside temperature, etc.) and terrain-related (nearby structures, trees, fences, etc.) has required the development of specialized monitoring equipment. Using sulphur hexafluoride as a tracer gas, using automated procedures for sending the gas into the building, and measuring the subsequent concentration decay, air infiltration has been measured for a wide range of circumstances. The details of the instrumentation presented here include: injection procedures, sampling methods, detection of the appropriate gas chromatograph concentration peak, and recording the data on magnetic tape for easy retrieval for computer calculations. The data resulting from such air infiltration instrumentation used are providing the basis for improved energy modeling in buildings, evaluation of energy conserving retrofits, new and old building inspection, and a better evaluation of other air infiltration measurement techniques.

8. Heggen, R., and Oehme, M., "Columns for Simultaneous Gas Chromatographic Determination of ppt Levels of the Atmospheric Traces Sulphur Hexafluoride and Bromotrifluoromethane in Ambient Air Samples", Journal of Chromatography 243(1), Pages 168-172, 1982.

> A detailed description of a method is given which allows the preparation of highly stable molecular sieve columns for trace analysis of SF_6 and $CBrF_3$ in ambient air samples. The simultaneous detection of about 5 ppt SF_6 and 100 ppt $CBrF_3$ in a 1 mL air sample is possible.

9. Grot, R.A., Hunt, C.M., and Harrje, D.T., "Automated Air Infiltration Measurements in Large Buildings", Presented at 1st Air Infiltration Centre Conf. Instrumentation and Measurement Techniques, Windsor, England, Oct. 6-8, 1980.

> An automated air infiltration measurement system for large buildings is described. The system consists of a micro-computer, electron capture gas chromatograph, a ten port sampling manifold, and five tracer gas injection units. The system controls the injection and sampling of tracer gas in a multi-zone building, calculates the air infiltration rates of each zone, and measures the on-time of events such as HVAC fan operation, exhaust fan operation, and door/window openings. The measurements also include such analog variables as interior and exterior temperatures, wind speed, wind direction and pressure differentials across the building envelope. The data collected using the automated air infiltration system in large buildings will allow the determination of the relative importance of air leakage and forced ventilation on the energy requirements of the building, as well as evaluating the influence of meteorological conditions, HVAC fan operation, exhaust fan operation and exterior building pressure on the air leakage.

10. Kalliokoski, P., Niemela, R., Salmivaara, J., "The Tracer Gas Technique - A Useful Tool for Industrial Hygiene", Scandinavian J. of Work Env. & Health, Vol. 6, No. 2, Pages 123-130, 1980.

> The tracer gas technique was applied in industrial hygiene surveys. Carbon dioxide, nitrous oxide, and sulfur hexafluoride were used to elicit ventilation rates and determine spreading routes of dilution air in the work environment. The continuous monitoring of nitrous oxide with an infrared spectrophotometer was found to be the most practicable choice for ventilation testing, whereas plastic bag sampling of nitrous oxide or sulfur hexafluoride with subsequent analysis by gas chromatography appeared to be a good method for emission spreading studies. The local flow rates of dilution air and the percentages of make-up air present were the most important information gained in the ventilation studies.

11. Kissell, F.N., Maksimovic, S.D., and Matta, J.E., "Method of Determining Gas Leakage through a Mine Stopping", U.S. Patent No. 4.,173,141, 1979.

> A method of determining the gas leakage through a mine stopping. The mine stopping, whose leakage is to be measured, is set up in a mine. Next, a test barrier is set up in the mine adjacent to the stopping. The volume between these two structures forms a closed test chamber filled with ambient gas. A known trace gas different from the ambient gas or a known contaminating gas is introduced into the chamber and mixed therin. Thereafter, periodic measurements are made of the rate of change in concentration of the tracer gas. Lastly, based upon the measured rate of change in concentration of the tracer gas, the leakage past the mine stopping is determined.

12. Kissell, F.N., and Bielicki, R.J., "Ventilation Eddy Zones at a Model Coal Mine Working Face", U.S. Bur. of Mines, RI 7991, 1974.

Tracer gas decay curves were experimentally obtained in a full-scale model coal mine working face area. The concentration of tracer gas was found to decay in exponential fashion but with a change in slope. This change in slope is attributed to eddy zones in the face area. A simple theory was developed that allows one to calculate the approximate amount of gas in the eddy zones and thus estimate the size of the eddy zones.

13. Kumar, R., Ireson, A.D., and Orr, H.W., "An Automated Air Infiltration Measuring System Using SF_6 Tracer Gas in Constant Concentration and Decay Methods", ASHRAE Transactions 85: 2, Pages 385-395, 1979.

One method of measuring rate of air infiltration in buildings involves the use of small amounts of a tracer gas. The concentration of the gas, which is measured at regular intervals, provides the basis for evaluating the infiltration rate. In the following paper, two bases for such evaluations are discussed in the decay method and the constant concentration method.

A system is described which automatically operates a portable electron capture detector/chromatograph and measures parts per billion concentrations of sulphur hexafluoride (SF_6) in air. It samples air on a 1-min. cycle. In the decay method, the slope of concentration vs time on a semilogarithmic plot can be used to compute the infiltration rate. In the second method, the system injects SF_6 at the rate required to maintain the tracer gas at a fixed, predetermined level. The infiltration rate is proportional to the rate at which the tracer gas must be injected.

14. Lamb, B.K., Vitols, V., and Skogvold, O., "Atmospheric Tracer Techniques and Gas Transport in the Primary Aluminum Industry", J. Air Pollut. Control Assoc., 30(5), Pages 558-566, 1980.

> The results of 35 individual SF_6 tracer tests conducted in Norway during 1978 demonstrate the applicability of tracer techniques to the study of a wide variety of pollutant transport problems found in the primary aluminum industry. Tracer methods were employed to determine the efficiency of the pollutant control system over a single reduction cell under a variety of operating conditions. Tracer investigations of flow in the wake of a smelter hall indicated that between 1% and 11% of secondary, roof-top emissions can become entrained in the recirculation cavity and re-enter the hall through the ventilation fresh air supply. Tracer dispersion data collected within 20 building heights of the smelter agreed very well with extrapolations of McElroy-Pooler dispersion curves for an urban area.
>
> The total fluoride mass flow rate measured downwind of a smelter during wet, foggy conditions indicated that wet removal rates of fluorides are in the range 3.2×10^{-4}/s to 6.4×10^{-4}/s. Simulation of the source with several tracer point releases and simultaneous measurement of fluoride and tracer ground-level concentrations downwind of the smelter eliminated the need for measurements of vertical profiles of wind speed and fluoride concentration during the experiment.

15. Lewtas, T.A., "Assessment of Induction Fan Effectiveness", U.S. Bureau of Mines, OFR 81-82, 1980.

> The work performed in this program was based on prior efforts using induction (jet) fans to ventilate dead

headings with the objective of refining the attachments to maximize fan effectiveness and to study the influence on the effectiveness of fan proximity to drift walls. Detailed anemometer surveys were designed to delineate the size and shape of the jet created by an induction fan, and tracer gas was used to determine the quantity of fresh air that an induction fan can deliver to the face of a drift and the fan's effectiveness in removing contaminants from the drift. Fan locations of 2 and 4 feet from the drift wall and at the drift center line were evaluated in the laboratory and all mine testing was done with the fan as close to the wall as possible. It was concluded that (1) an aerodynamic nozzle increases jet penetration and any tubing length up to 15 feet, (2) locating the fan near the drift wall increases jet penetration, (3) air flow straighteners are ineffective in increasing penetration, and (4) induction fan installations in general are ineffective in removing contaminants from dead headings without sufficient main ventilation flow.

16. Lipschutz, R.D., Dickinson, J.B., and Diamond, R.C., "Infiltration and Leakage Measurements in New Houses Incorporating Energy Efficient Features", U.S. Dept. of Energy LBL-14733, 1982.

Measurements of leakage areas and infiltration rates in houses incorporating energy-conserving measures can provide important information about their effectiveness. Houses with energy efficient designs in Eugene, Oregon and Rochester, New York were measured for effective leakage area using blower door fan pressurization. Air exchange rates were determined by tracer gas decay analysis. Fan pressurization measurements were made on 13 new houses in the San Francisco Bay area that had been partially sealed with polymeric foam sealant. A similar group of 13 new

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houses that had not been sealed were measured as controls. The results of these measurements were used in conjunction with an infiltration model developed at Lawrence Berkeley Laboratory to predict average annual and heating season infiltration rates.

17. Matta, J.E., Thimons, E.D., and Kissell, F.N., "Jet Fan Effectiveness as Measured with SF_6 Tracer Gas", U.S. Bur. Mines RI 8310, 1978.

The Bureau of Mines conducted tests using a tracer-gas technique to measure the effectiveness of the jet fan, which is often employed in mines to ventilate dead headings.

Results of these tests show that jet fans can (1) ventilate dead headings beyond the maximum penetration distance indicated by smoke-tube detection of air movement, and (2) redistribute available fresh air through larger working areas. However, if the fresh air base is insufficient, the fan will merely recirculate the contaminated air and disperse it over a larger volume.

18. Matta, J.E., Maksimovic, S.D., and Kissell, F.N., "Tracer Gas Method for Measuring Lekage through Mine Stoppings", U.S. Bur. of Mines RI 8324, 1978.

The Bureau of Mines has developed a tracer gas method for measuring leakage through permanent mine stoppings. In this method, a temporary brattice is erected in the same entry as the leaking permanent stopping. Leakage was evaluated from concentration measurements of a tracer gas introduced into the space between the stopping and brattice. Stopping leakages ranging from 15 cfm to 265 cfm were simulated in an underground coal mine. Leakage values determined by the new method were within 10 pct of the known values.

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19. Thimons, E.D., and Kissell, F.N., "Tracer Gas as an Aid in Mine Ventilation Analysis", U.S. Bureau of Mines RI 7917, 1974.

> Sulfur hexafluoride (SF_6), has been used successfully as a trace gas to measure mine air flows under conditions where conventional methods have failed. SF_6 has been employed experimentally to: Measure accurately recirculation of return into intake air caused by leakage through an old stoped area; check for potential leakage from an adjacent mine; trace 10,000 cfm of "lost" air from an intake airway; and measure transit air times through uranium mines. It has proved useful as a means of accurately measuring airflow volumes in airways of large cross-section and very low flow velocity, and in determining the recirculation resulting from underground cooling plants.

20. Thimons, E.D., Bielicki, R.J., and Kissell, F.N., "Using Sulphur Hexafluoride as a Gaseous Tracer to Study Ventilation Systems in Mines", U.S. Bureau of Mines RI 7916, 1974.

> Sulfur hexafluoride (SF_6), released from a lecture bottle, was found to be an ideal gaseous tracer for studying mine ventilation systems. Air samples, collected in glass syringes, were analyzed by means of the technique of electron-capture gas chromatography. In these studies, the lower limit of detection was about 1 part per billion by volume (ppb) of SF_6 per part of air.
>
> Experiments conducted in a Pennsylvania limestone mine showed this technique useful in evaluating the effectiveness of auxiliary fans, measuring low flow velocities, probing the air circulating near a working face region where ventilation appeared to be poor, and

estimating volumetric flow rates in airways of large cross-sectional area and having low flow velocities. This technique was also used in a Western metal mine to measure the amount of return air being recirculated into the intake air due to leakage through old stoped areas.

21. Vinson, R.P., and Kissell, F.N., "Three Coal Mine Ventilation Studies using Sulfur Hexafluoride Tracer Gas", U.S. Bureau of Mines RI 8142, 1976.

This report describes three coal mine ventilation studies by the Bureau of Mines in which SF_6 was used as a tracer gas. One of these studies was conducted to determine air movement and leakage in a sealed area. Another was run to determine the ventilation efficiency of a bleeder system. Finally, a study was made of air leakage across permanent stoppings of parallel intake airways. These studies proved sulfur hexafluoride to be a useful addition to the equipment commonly used in coal mine ventilation analysis.

22. Vinson, R.P., et al, "Face Ventilation Measurement with Sulfur Hexafluoride (SF_6"), U.S. Bur. of Mines RI 8473, 1980.

The face ventilation measurement method developed by the Bureau of Mines involves releasing a small volume of tracer gas (SF_6) on the off-curtain side of the working face at the start of the mining cycle. At the same time, gas bottle samples are taken in the immediate return airway. The gas samples are analyzed, and a curve is drawn of SF_6 concentration versus time. From this curve, the percentage of gas removed per time is calculated. A curve showing a high percentage of the tracer gas removed in a short period would represent a well-ventilated face.

The face ventilation measurement method was tested in a full-scale mine entry model. Subsequently it was used underground to evaluate the spray-fan ventilation system and in an MSHA test facility to test machine-mounted scrubbers. The method was shown to be a simple and effective way of evaluating face ventilation systems.

23. Vinson, R.P., Volkwein, J.C., and Thimons, E.D., "SF_6 Tracer Gas Tests of Bagging=Machine Hood Enclosures", U.S. Bur. of Mines RI 8527, 1981.

This Bureau of Mines report presents the results of tracer gas studies conducted at three facilities where bagger hoods had been installed several years ago to remove airborne silica dust from the vicinity of the bagging operator. The studies indicated that for optimum benefits makeup air must be evenly dispersed, the hood enclosures and duct systems must be as airtight as possible, the average intake air velocity of each hood should be at least 200 fpm, and the hoods and duct systems must be properly maintained.

24. Wann, J.M.R., Milner, A., and Wynne, A., "Some Practical Experiences using Sulphur Hexafluoride as a Tracer Gas to Determine Leakage Rates in Mine Ventilation Systems, Mainly in the South Nottinghamshire Area", Mining Engineer 136(191), Pages 391-404, 1977.

Sulphur hexafluoride has been used as a tracer gas to determine air leakage rates between shafts of neighbouring collieries, through old workings, and to measure leakage rates through stoppings.

Both steady release and pulse release techniques have been used.

The physical characteristics of sulphur hexafluoride, coupled with a lower limit of detection of approximately 1 part in 10^{12} using the electron capture detector, indicate that it is likely to be superior to other gases which have previously been used as tracers. Some of its advantages have been demonstrated in a number of practical exercises underground, under varying conditions.

25. Condon, P.E. et al., "An Automated Controlled-Flow Air Infiltration Measurement System", Presented at Symp. on Air Infilt. and Air Change Rate Meas., Washington, D.C., March 13, 1978.

A description is presented of an automated, controlled-flow air infiltration measurement system. This system measures total air flow, a volume per unit time, due to infiltration in a test space. Data analysis is discussed and the mixing problem is analyzed. Different modes of operating the system are considered: (1) concentration decay, (2) continuous flow in a single chamber and (3) continuous flow in a multichamber enclosure. Problems associated with the use of nitrous oxide as a tracer gas are described.

26. Harrje, D.T., Grot, R.A., and Grimsrud, D.T., "Air Infiltration Site Measurement Techniques", Presented at 2nd AIC Conf. Building Design for Min. Air Infilt., Stockholm, September 21-23, 1981.

A summary of the existing types of air infiltration measurement techniques and instrumentation using tracer gases is presented. Automated air infiltration instrumentation used by researchers in the United States, Canada, the United Kingdom, Denmark, Sweden and Switzerland are described. The equipment can operate in the dilution (decay) mode, constant flow mode and the constant concentration mode. Most of these instruments are microcomputer or microprocessor based and capable of performing real time determination of the air infiltration rate in multizone buildings and monitor the state of additional parameters such as temperature, wind speed and energy consumption. Two simple techniques, the air bag or container method and the average infiltration monitor, developed by researchers in the United States are summarized.

27. Kronvall, J., "Air Tightness - Measurements and Measurement Methods", Swedish Council for Building Research, Stockholm, ISBN-91-540-3201-6, 1980.

This paper describes different methods of measuring the airtightness of whole buildings, and reproduces the greater part of the results of measurements which have been made in different places, primarily using the pressure method but also using the tracer gas method to some extent. The pressure method is described together with the recommended method (SP 1977:1) published by the National Swedish Authority of Testing, Inspection and Meteorology, which is explained and commented upon where necessary. A number of variations of the tracer gas method, as used for measuring the ventilation in a building, whether continuously or occassionally, are described, together with descriptions of suitable equipment.

28. Sandberg, M., and Svensson, A., "Measurements of Ventilation Efficiency by Using the Tracer Gas Technique", Building Services Engineering Res. and Technol., Vol. 2, No. 3, Pages 119-126, 1981.

The local ventilation efficiency of a mechanical ventilation system may in general terms be defined as 'providing air in those parts of a room where it is required'. In this paper different definitions of the local efficiency and methods for measuring it are discussed. Finally, results from measurements of the ventilation efficiency are presented. These indicate that, in some cases, only a minor proportion of the ventilation air flow is utilised in the occupied zone. Furthermore it is demonstrated that it is normally not advisable to use the slope of the tracer gas curves in a linear logarithmic plot as a measure of the 'local ventilation rate'. The slopes will normally, after a certain period of time has elapsed, become equal. Then they reflect only the overall ventilation rate and not local differences.

29. Sandberg, M., "What is Ventilation Efficiency?", Building and Environment, Vol. 16, No. 2, Pages 123-135, 1981.

Various definitions of ventilation efficiency are examined. When using tracer gas techniques the definitions of a ventilation system's efficiency can be based on the slope of the tracer gas curves, or the ratio between concentrations, or the area under the curves. The consequences of these definitions are examined for a simple theoretical model. Experimental measurement on a test room are presented which show that sometimes very low ventilation efficiency can occur.

30. Breslin, J.A., and Strazisar, A.J., "Dust Control Studies Using Scale Models of Coal Mine Entries", U.S. Bureau of Mines RI 8191, 1976.

Three scale models of coal mine entries and mining machines were constructed and used by the Bureau of Mines to study the effects of ventilation parameters on dust concentrations where mining personnel would be working. A

1/5 scale model of a coal mine entry with a drum type continuous mining machine and a 1/6 scale model of an entry with a twin borer type machine were used as well as a 1/5 scale model of a longwall face with a double drum shearer. Methane was used as a tracer gas to simulate respirable dust in the models. The distance of the end of the brattice or tubing from the face was found to be more important than the air flow rate for the drum type machine. Dust reductions greater than 90 percent were shown to be possible with a secondary ventilation system used with the twin borer and dust collector mounted on the longwall shearer. Cutting head speed has a significant effect on concentrations at typical positions of miners with the drum type machine and longwall shearer but not for the twin borer.

31. Wippern, D., et al., "Characterization of Fluidized Bed Reactors with Gas Tracer Measurements", Chem. Eng. Commun., Vol. 16, No. 4/5, Pages 307-330, 1981.

In a steady state bench scale fluidized bed the decomposition reaction of $NaHCO_3$ was carried out. The residence times distributions, DRT, of carbon dioxide (the gaseous product) and non adsorbing argon (the reference tracer) were mass spectroscopically measured as a function of the bed temperature. By means of single-, two- and three-phase dispersion models as well as by a cell model, the DRT's were evaluated on line by a computer.

The steady state transverse and longitudinal concentration profiles of these tracers upstream from the plane source were also measured and evaluated by a dispersion model as well as by a counter current back mixing model.

The on-line DRT can be used as a diagnostical technique for investigation of the reactor during its operation, if operation disturbances or breakdowns occur.

32. Danner, R.P., Nicoletti, M.P., and Al-Ameeri, R.S., "Determination of Gas Mixture Adsorption Equilibria by the Tracer-Pulse Technique", Chemical Engineering Science, Vol. 35, No. 10, Pages 2129-2133, 1980.

A chromatographic technique using radiotracer gases has been used to determine pure gas isotherms and gas mixture adsorption equilibria over the entire concentration range. The ethane-ethylene-Molecular Sieve Type 13X and pure carbon monoxide-Molecular Sieve Type 5A systems were studied. The data obtained by this dynamic technique are shown to be in agreement with data obtained previously by a static (volumetric) method. The chromatographic method is much more efficient for obtaining mixture data and is considerably easier to adapt to wider pressure and temperature ranges than static methods.

33. Osborne, M.C., Ledbetter, J.O., and Atkins, P.R., "Downwash of Gas Vented from Top of Cubical Building Model", American Industrial Hygiene Association Journal 43(6), Pages 466-469, 1982.

This study was done to determine the validity of existing techniques for describing the downwash concentrations resulting from building emissions through flush vents. A low-speed wind tunnel was used with a building model and anhydrous ammonia tracer gas to simulate ambient prototype conditions. Concentrations were measured in a plane one inch above the floor of the tunnel and downwind of the one foot, cube shaped, model building. From the concentration data, a position constant was assigned to each sampling point according to an equation developed by Halitsky. The results showed that downwash concentration prediction is possible by Halitsky's equation only when the wind is directed into a face of the structure.

34. Thimons, E.D., Maksimovic, S.D., and Kissell, F.N., "Correction Factors for Low-Velocity Airflow Measurements in Mines", U.S. Bureau of Mines RI 8400, 1979.

The Bureau of Mines conducted in-mine tests to determine correction factors applicable to low-velocity airflows (below 150 fpm) measured by the smoke cloud, vane anemometer, and oil of wintergreen tracer gas techniques.

All tests measured airflows with controlled average velocities ranging from 50 to 100 fpm. Correction factors averaged about 0.75 for readings taken by the centerline smoke cloud method, remotely controlled and stickheld centerline anemometer, and split traverse stick-held anemometer. For hand-held centerline anemometer and oil of wintergreen tracer gas readings, correction factors averaged about 0.67.

Smoke and oil of wintergreen give results as consistent as those obtained with specially calibrated, low-velocity anemometers. Furthermore, they are easy to use and inexpensive.

35. Dietz, R.N. et al., "An Inexpensive Perfluorocarbon Tracer Technique for Wide-Scale Infiltration Measurements in Homes", Presented at Int. Symp. on Indoor Air Pollut., Health and Energy Conserv., Amherst, Mass., Oct. 13-16, 1981, BNL 30032, Brookhaven National Laboratory, Upton, NY.

> A perfluorocarbon tracer technique to determine infiltration rates in homes is described. A tracer kit, coined the Brookhaven National Laboratory Air Infiltration Measurement System, which can be deployed by the average homeowner is briefly described. The tracer source is a fluoroelastomer plug impregnated with a known mass of perfluorocarbon tracers (PFT) and crimped within a metal shell. The PFT diffuses from the end of the plug. Two samplers briefly described are: the capillary adsorption tube sampler (CATS) and the programmable Brookhaven Atmospheric Tracer Sampler (BATS). Deployment of one of the diffusion sources in a home and use of a BATS unit to measure the increase in the tracer concentration perfluorodimethylcyclohexane (PDCH) are discussed. Results of the tests are presented.

36. Dietz, R.N., and Cote, E.A., "Tracing Atmospheric Pollutants by Gas Chromatographic Determination of Sulphur Hexafluoride", Env. Sci. Technology, 7:338, 1973.

> Dietz, R.N., and Cote, E.A., "Tracing Atmospheric Pollutants by Gas Chromatographic Determination of Sulphur Hexafluoride", Env. Sci. Technology, Vol. 7, Page 338, 1973.

37. Simmonds, P.G., Lovelock, A.J., and Lovelock, J.E., "Continuous and Ultrasensitive Apparatus for the Measurement of Airborne Tracer Substances", J. Chromatography 126:3, 1976.

38. Sinden, F.W., "Multi-Chamber Theory of Air Infiltration", Building and Environ., Vol. 13, No. 1, Pages 21-28, 1978.

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REPORT P-4331/G-1

Tracer Gas Review and Tracer Gas Ventilation Study of a Tunnel Boring Machine

Phase 2: Ventilation Test Program

for

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1. SOMMAIRE

Les essais en usine d'une perforatrice-excavatrice blindée (PBT) pour le creusement de tunnels, mesurant à l'avant 7,6 m de diamètre, conçue et construite par la firme Lovat Tunnel Equipment Inc., furent menés durant les mois d'avril à juin 1983, dans les bâtiments de cette firme à Rexdale en Ontario. Au terme de ces essais en usine, la Corporation de Développement du Cap Breton (CDCP) prenait livraison de cette machine et prévoyait la mettre en service plus tard cette année.

Au cours des dernières années, les expériences effectuées sur le fonctionnement de machines semblables dans les mines de houille ont montré que l'inflammation du méthane par suite de frictions peut survenir au niveau de la partie avant ou tête de perçage de la perforatrice-excavatrice. On attribue la cause principale des explosions antérieures de méthane à une ventilation insuffisante de la partie avant de telle machine, ce qui y occasionnait une accumulation de ce gaz. Voilà les raisons qui ont amené le Centre canadien de technologie minière et énergétique (CCTME), du ministère de l'Énergie, des Mines et des Ressources naturelles (EMRN), à évaluer le système de ventilation de la tête de ces énormes PBT et ce, par le biais d'épreuves en usine utilisant des techniques appropriées de traçage au gaz.

Conformément à ses engagements contractuels, l'Ontario Research Foundation (ORF), un organisme provincial voué à la recherche, entreprit d'abord l'examen des gaz-traceurs disponibles et passa en revue les différentes méthodes techniques employées dans d'autres études; elle sélectionna ensuite les

techniques les mieux adaptées pour les utiliser dans l'évaluation dudit système de ventilation, conformément à un protocole établi par le CCTME, l'ORF et Lovat. L'étude comporta deux phases lesquelles, en raison d'échéances rapprochées ayant trait à la livraison de la PBT, furent menées simultanément. La phase 1 porta sur l'examen des diverses méthodes techniques et sur la sélection d'une méthodologie; la phase 2 engloba les divers essais sur le système de ventilation de la machine.

Le présent rapport fait le sommaire des différents aspects de l'étude, comme suit: objectifs, préparatifs de l'emplacement, protocole d'essais, ajout de gaz-traceurs, méthodes analytiques et d'échantillonnage, résultats des essais, évaluation des données et conclusions de la phase 2.

Objectifs

l'objectif primordial de l'étude a consisté à déterminer l'efficacité du système de ventilation à évacuer le méthane, qui se trouve au niveau de la tête de perçage de la PBT. D'autre part, les évaluations des effets de l'évacuation du méthane à des paramètres de fonctionnement différents de la PBT, celles de la structure de la tête de perçage et celles des points d'ajout de traceur furent reléguées parmi les objectifs secondaires.

Préparatifs de l'emplacement

Dans le but de simuler une paroi de rocher, on dressa à l'avant de la machine, à quelques centimètres des lames, un écran construit à partir d'un châssis en acier dans lequel s'inséraient des panneaux de plexiglass. Vingt-deux points devant servir à l'ajout des gaz-traceurs furent déterminés à différents endroits sur la surface de l'écran, lequel fit aussi l'objet d'un éclairage plus fort nécessaire à l'enregistrement des essais spécifiques sur films magnétoscopiques. Des ventilateurs autonomes à conduit flexible ont assuré le refoulement et l'échappement de l'air à l'intérieure de la tête de perçage.

Protocole d'essais

Plusieurs séries d'essais avec gaz-traceurs furent menées en fonction de tous les points d'ajout de traceur ou en fonction de points d'ajout spécifiques; de plus, ces essais ont différé les uns des autres et ont comporté au moins l'un des paramètres suivants: taux de refoulement et d'échappement de l'air en fonction du sens de rotation et de la vitesse rotatoire de la tête en mode stationnaire. Ces séries d'essais furent suivis de tests avec grenades fumigènes pour l'évaluation visuelle de la ventilation à l'intérieur de la tête. Ces derniers essais furent filmés sur bandes magnétoscopiques.

Méthodologie

Du gaz propane a servi de traceur dans la plupart des tests. Un déclencheur actionné au moyen d'un solénoïde injecta, à raison de 150 cc par impulsion, ce gaz à partir d'une bonbonne fixée à même la surface de l'écran. Aux fins de l'étude, d'autres traceurs, notamment du méthane et de l'hexafluorure de soufre, furent utilisés. Des échantillons représentatifs d'air furent prélevés dans le conduit d'échappement de la tête de perçage et analysés "in situ" au moyen d'un analyseur-totalisateur d'hydrocarbures, d'un détecteur d'ionisation de flamme et d'un spectomètre infrarouge Miran. Les concentrations de gaz à l'échappement furent relevées dès l'injection du traceur et jusqu'à l'obtention de concentrations nulles. Un enregistreur a relevé graphiquement les donnés obtenues par traçage, tandis qu'un intégrateur interprétait ces données pour le rapport d'évaluation.

Résultats des essais

Dix essais fumigènes furent enregistrés sur rubans couleurs magnétoscopiques et des films en furent tirés par la suite. L'effet de la rotation de la tête de perçage sur la configuration de la circulation de l'air à l'intérieur de cette partie de la machine se manifesta clairement à l'issue de ces essais. Plusieurs centaines de concentrations de traceur furent relevées par rapport à des courbes temporelles et furent réinterprétées sous forme de diagrammes au moyen d'un enregistreur et d'un intégrateur; ces résultats compilées figurent au rapport, en annexes distinctes. Ce rapport comporte également des croquis à l'échelle sur la plupart des traçages. Ces croquis montrent les effets de la rotation de la tête de perçage et des taux de circulation de l'air.

Évaluation des données

Pour chacun des points d'ajout de gaz-traceur et pour chacune des expériences exécutées, une courbe fut tracée afin de déterminer le pourcentage de traceur évacué de la tête de la machine dans un temps donné. C'est habituellement quelques secondes après l'ajout du traceur que les instruments l'ont détecté au point d'échantillonnage. L'évacuation complète du traceur de la tête s'effectua en moins d'une minute. Le taux d'évacuation du traceur selon le temps a varié pour chacun des points d'ajout:

c'est aux points d'ajout situés dans le périmètre de l'écran que furent relevées les résultats initiaux de ventilation les plus lents. En effet, l'évacuation des gaz au niveau de ces points a donné les taux les plus bas en raison d'un refoulement d'air nul et d'un échappement minimal dans cette région.

Les diagrammes isopleths tracés d'après les concentrations de traceurs obtenues sous diverses conditions de fonctionnement de la PBT ont dénoté certains effets attribuables à la rotation de la tête de perçage, à la circulation de l'air ventilé par le système et à la structure de la tête. Lorsque la tête de perçage était en position stationnaire, le système de ventilation fut plus efficace à évacuer le traceur dans l'axe haut-bas le long de la surface de l'écran et également dans le quadrant inférieur gauche. Sous l'effet de la rotation de la tête, on a noté des concentrations de gaz sur un axe de biais dans toutes les circulations d'air, sauf dans les valeurs maximales où la configuration des concentrations de traceur s'avéra très symétrique. L'interprétation des traçages au moyen de simples modèles mathématiques s'est révélée une tentative insatisfaisante, étant donné que les courbes décroissantes des concentrations de traceurs étaient indépendamment affectées par plusieurs paramètres. L'application de techniques informatisées aurait facilité l'interprétation théorique.

Conclusions

Les principales conclusions tirées des données recueillies lors du programme d'essais dudit système de ventilation sont les suivantes:

- Le système de ventilation de la PBT évacue assez rapidement les gaz qui y pénètrent dans la plupart des conditions de ventilation et à tous les points au niveau de la surface de la tête de perçage.

- L'évacuation des gaz s'effectue le plus lentement en présence d'un refoulement d'air nul, d'un échappement minimal et d'une fuite au niveau du rebord de la tête de perçage. Ces conditions peuvent favoriser l'accumulation de méthane à des taux inacceptables le long du rebord de la tête de perçage.

- La vitesse rotatoire de la tête perçage, la direction de son déplacement de même que sa structure interne et la position de ses lames en mode de fonctionnement stationnaire sont des paramètres qui influent sur la configuration des concentrations de traceur par rapport aux courbes de temps, sans toutefois affecter significativement les taux d'évacuation des gaz à des rythmes de ventilations spécifiques.

- Les méthodes de traçage au gaz utilisées dans la présente étude sont fiables et convenables, en plus de s'avérer un moyen efficace d'évaluer les systèmes de ventilation des têtes de perforatrice-excavatrice de tunnels.

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1. EXECUTIVE SUMMARY

Shop floor testing of a 7.6 m diameter shielded full-face tunnel boring machine (TBM), designed and constructed by Lovat Tunnel Equipment Inc., was conducted during April - June, 1983, at the Company's facilities in Rexdale, Ontario. Following completion of shop floor trials the machine was delivered to the Cape Breton Development Corporation (CBDC) for service later in the year.

In recent years operational experience of such machines in coal mines has shown that frictional ignitions of methane gas may occur in the machine head. Inadequate head ventilation, allowing methane concentrations to build up in the head, is considered to be the major reason for previous explosions. For this reason, therefore, the Canada Centre for Mineral and Energy Technology (CANMET), Department of Energy, Mines and Resources (EMR), decided to assess the head ventilation system of the large TBM during shop floor trials, using appropriate tracer gas techniques.

Ontario Research Foundation (ORF) were contracted to review available tracer gases and methodologies used in other studies, select the most suitable techniques, and use them to assess the head ventilation system according to a protocol to be established by CANMET, ORF and Lovat. The study was divided into two phases, which, because of time constraints related to delivery of the TBM, were conducted concurrently. Phase 1 included the methodology review and selection and Phase 2 covered the head ventilation tests program.

This report provides details of the objectives, site preparation, test protocol, tracer gas addition, sampling and analytical methods, test results, data assessment and conclusions for Phase 2 of the study.

Objectives

The primary study objective was to determine the effectiveness of the TBM head ventilation system in removing methane from the head area. Secondary objectives included an assessment of the effects on methane removal of varying TBM operating parameters, head structure and tracer addition location.

Site Preparation

In order to simulate the rock face a shroud, constructed of steel framework and plexiglass panels, was placed over the machine head within a few centimeters of the cutter blades. Twenty-two tracer gas addition points were located on the shroud face which was illuminated by additional lighting for videotaping of specific tests. Separate fans with flexible ducting provided required forcing and exhaust air flows in the TBM head.

Test Protocol

Several series of tracer gas tests were conducted for all or specific addition points, varying one or more of such parameters as forcing and exhaust air flowrates and head rotational speed and direction; or head position in a stationary mode. These test series followed videotaping of smoke bomb tests to visually assess the head ventilation.

Methodologies

Propane was used as the tracer gas for most tests and was injected as a 150 cc pulse by solenoid activated release from a pressurized bomb attached directly to the shroud face. Other tracers such as methane and sulphur hexafluoride were also evaluated. Representative air samples were withdrawn from the head exhaust air duct and analyzed in-situ by a total hydrocarbon analyzer, with flame ionization detector, and also a Miran infra-red spectrometer. Exhaust gas concentrations were monitored from the moment of the tracer injection until concentrations decayed to zero.

Traces were recorded by chart recorders and also by a reporting integrator to provide data for evaluation.

Test Results

Ten smoke bomb tests were recorded on colour videotape, from which films were subsequently made. The effect of head rotation on air flow patterns within the head is readily apparent from these tests. Several hundred tracer gas concentration versus time curves were recorded and charts for each test from recorder and integrater have been compiled into separate appendices to the report. Scaled drawings of most traces are presented in the report showing the effects of head rotation and air flow-rates.

Data Assessment

For all addition points curves were plotted from traces to determine the percentage of tracer gas removed from the head with time. Tracer was usually detected at the sampling location within a few seconds after addition to the head and totally removed from the head within one minute. The rate of tracer gas removal with time varied for each addition location, with gas added at locations close to the shroud face perimeter showing the slowest initial response. Gas removal is slowest at these locations when there is no forcing air and minimum exhaust air flow.

Tracer gas concentration isopleths drawn for various TBM operating conditions indicate effects due to head rotation, ventilation flow and head structure. With zero head rotation ventilation is more efficient at removing tracer gas along the top to bottom axis of the face and also to the lower left of centre. With rotation a skewed effect of concentration is noted for all air flows except for maximum values when the concentration pattern is very symmetrical. Attempts to interpret traces by simple mathematical models were not satisfactory since the tracer gas concentration decay curves are affected by several parameters interdependently. Theoretical interpretations would be aided by the application of computer techniques.

Conclusions

Major conclusions drawn from all data collected from the ventilation test program are as follows:

- The TBM ventilation system removes gas leaking into the head fairly rapidly for most ventilation conditions and at all locations across the head face.

- Gas removal is slowest with no forcing air, minimum exhaust air flow and leakage at the edge of the head face. These conditions may allow methane build-up at the edge of the head to unacceptable levels.

- Parameters such as head rotational speed and direction, internal head structure and position of cutter blades with no head rotation effect the shape of tracer gas concentration versus time curves, but do not significantly affect gas removal rates for specific ventilation air flows.

- Tracer gas methods used in this study were reliable, appropriate and provide an effective means of assessing TBM head ventilation systems.

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2. INTRODUCTION

Operational experience of tunnel boring machines (TBM) in specific coal fields has shown that frictional ignitions of methane in the head area can and do occur. This is usually a result of inadequate head ventilation allowing methane concentrations to reach unacceptable levels at the face. For this reason, therefore, the Canada Centre for Mineral and Energy Technology (CANMET), Department of Energy, Mines and Resources (EMR), agreed to evaluate the head ventilation system of a new large TBM being built by Lovat Tunnel Equipment Limited. The machine is being constructed and evaluated at Lovat's facilities in Rexdale, Ontario, prior to delivery to the Cape Breton Development Corporation (CBDC) in the summer of 1983 for service in the latter part of the year.

In mid-April of 1983 a contract was awarded to the Ontario Research Foundation (ORF) to carry out an extensive test program to assess the TBM head ventilation system, using appropriate tracer gas techniques. It was originally intended that the study would be conducted in two successive phases. The initial phase would be a literature review and assessment of tracer gas addition, sampling and analysis techniques, with subsequent selection of methodologies appropriate for this study. Phase 2 would then entail use of the selected methodologies to assess the head ventilation system, during shop floor trials of the TBM, according to a protocol to be established by CANMET, ORF and Lovat. However, since the head ventilation evaluation program was only one item of a series of trials, dictating the delivery date of the TBM, and was scheduled for a specific two week period in May, it was realized that there was insufficient time to complete Phase 1 before initiating Phase 2.

A decision was made, therefore, to select appropriate tracer gas techniques on the basis of ORF's knowledge of, and experience with, available methodologies, allowing time for some laboratory evaluation of proposed methods and preparation and calibration of all necessary equipment.

At the same time a literature search was initiated and the review and assessment of published information was scheduled to be completed after the shop floor ventilation test program. The latter commenced on the evening of May 16, 1983 and proceeded during evening and night shifts on twelve consecutive days, ending on May 27, 1983.

The following sections of this report, on Phase 2 of the study, present program objectives and test protocol, give brief descriptions of the TBM and test site, provide details of all methodologies employed, summarize all information and data collected and discuss the ventilation effectiveness based on results obtained. The actual chart recordings from the several hundred tracer gas tests made during the field program have been submitted in a separate appendix to the Scientific Authority. The literature search and review, together with laboratory evaluations of specific tracer gas techniques, will be submitted as a separate report on Phase 1 of this study.

3. PROJECT OBJECTIVES

The primary objective of this study was as follows:

- to determine the effectiveness of the TBM head ventilation system in removing methane from the head area.

The work program was conducted in two separate phases, each of which required specific objectives to be met in order to achieve the primary study objective. These secondary objectives are listed below:

Phase 1

- to review candidate tracer gases and tracer gas addition, sampling and analytical systems.
- to select appropriate tracer gas methods applicable to the needs of this study.

- to evaluate selected methods in the laboratory and to demonstrate their suitability.

Phase 2

- to carry out an extensive series of tracer gas tests during TBM shop floor trials according to a protocol established by the Scientific Authority.
- to complete the entire test program within the time frame allowed for ventilation tests.
- to show the effects of various parameters such as forcing air and exhaust air flowrates, head rotation speed and direction and point of methane leakage into the head on methane removal.

4. MACHINE DESCRIPTION

The 7.6 m diameter shielded full-face tunnel boring machine (TBM) was designed and constructed by Lovat Tunnel Equipment Inc. and located at their plant in Rexdale, Ontario. In order to effect realistic positional and operational relationships of TBM and ancilliary platforms plus equipment, the main body of the machine was supported in a well several feet below shop floor level. Figure 1 and Figure 2 provide front-side and rear-side views of the TBM in location for shop floor trials prior to installation of ventilation ducts. An angled view of the TBM cutter head and a view from the shop floor behind a platform containing operating equipment are shown in Figure 3 and Figure 4 respectively.

Operating controls for the TBM are located adjacent to a small operating platform situated immediately behind the cutter head to the right of the centre, as seen in Figure 5. The TBM is designed to bore underground at a rate of up to 3 metres per hour, depending on face conditions, and the cutter head may be rotated in either direction at speeds up to four revolutions per minute. Material cut from the face by the action of the disc cutters falls through the head between blades onto collection plates and is then deposited during head rotation onto a conveyor and removed from the TBM. The conveyor associated with the machine is seen protruding from the machine core in Figure 2.

Ventilation within the TBM is effected by a forcing fan supplying air at a flowrate of up to 4.72 m^3/s through ducting connected to machine ducts by flexible tubing. This air passes into the cutter head region through two 0.47m diameter holes at the top of the TBM immediately behind the rotating head. Air is exhausted by an extracting fan through four ports in a central region behind the rotating head (the conveyor hole) at a total flowrate of up to 7.08 m^3/s. Top and side views of the proposed ventilation system layout are given in Figure 6, illustrating the orientation of forcing air and exhaust ducts and giving maximum air flows. During shop floor trials flexible tubing and fans were used to provide the required forcing and exhaust air flows. The forcing air fan was located above the conveyor belt as shown in Figure 7. Exhaust air was removed via flexible tubing by an extracting fan located outside the plant building as seen in Figure 8.

A scale drawing of the cutter head face is given in Figure 9 illustrating the blade arrangements. The disc cutter placements on the eight full and eight half blades is complex, but they essentially form a spiral pattern from the centre to the outside of the face. Figures 10, 11 and 12 show the spaces between blades at the head face, the sequence of holes in the back plate of the rotating head and the position of forcing and exhaust air vents immediately behind the head, respectively. An overlay of these figures illustrates the spacial arrangement throughout the head when stationary during the test program, thus showing potential channels for air flow (see Appendix A).

For the test program to assess the ventilation system a shroud was constructed to cover the entire cutter head face simulating, as closely as possible, actual operating conditions underground. A steel frame was built to house 1.2 m x 1.2 m plexiglass panels. The entire structure was fixed closely to the cutter head affording clear observation of the face and introduction of tracer gas through ports placed at different locations across the shroud. Figure 13 shows the finished structure with tracer gas being introduced at the top of the shroud. Figure 14 clearly shows the shroud framework and the marked blade on the cutter head which was used when rotating to determine when tracer gas should be injected within the shroud. The locations of tracer gas injection points on the shroud face are shown in Figure 15.

5. METHODOLOGY

Four separate analytical systems were used in the field tests at the Lovat shop. These analytical systems, and the methodologies for tracer injection, as well as the procedure used for the smoke bomb tests are described in the following sections.

Analytical Equipment

Two Ratfisch Model RS5 total hydrocarbon analysers were used in the shop floor trials, one routinely and the other available as a back-up. The RS5 THC analyzer utilizes a flame ionization detector for measuring concentrations of hydrocarbons from 0.1 ppm to 10,000 ppm as CH_4, over four operating ranges: 0 - 10 ppm, 0 - 100 ppm, 0 - 1,000 ppm and 0 - 10,000 ppm. A calibration gas of 29.8 ppm propane in nitrogen (certified standard - Matheson) was used to calibrate the analyzer. "Ultra zero" grade air (THC certified to less than 0.1 ppm as CH_4) and "zero" hydrogen were used for burner combustion air and fuel respectively.

Output from the analyzer is a 0 - 10 V signal. A Hewlett Packard Model 3155B chart recorder was used to record the analyzer response. The fastest chart speed on the recorder, 10 seconds per centimeter, was used for all traces in order to provide the clearest possible record of the fast analyzer response. For most tests a Hewlett Packard Model 3390A reporting integrator was also connected to the analyzer output. This provided data on the area under the observed trace, as well as the time of peaks. In order to accommodate the maximum voltage input to the integrator (1 V), the THC analyzer was operated in the 0 - 100 ppm range for most tests, with the chart recorder set at 0.1 V per cm, so that the full scale reading on the chart was 10 ppm. For peaks that went off scale at this setting, either the recorder voltage setting or the THC analyzer range setting was switched to obtain a reading on scale.

A Miran 1A Portable Gas Analyzer was used as a secondary analysis system for propane. The Miran analyzer is a single beam, variable filter spectrometer, scanning the infra-red spectral range between 2.5 μm and 14.5 μm. It has a gas cell having a pathlength variable between 0.75 metres and 20.25 metres. For propane analysis the wavelength was set at 3.45 μm and the pathlength was 0.75 m. A carbon vane vacuum pump was used to draw sample gas through the analyzer. This pump has a higher capacity than the built-in pump on the analyzer and therefore reduces the response time. Output from the analyzer was recorded on a Hewlett Packard Model 3155B chart recorder, operated at 10 seconds per centimeter or 30 seconds per centimeter.

For some preliminary trials SF_6 was tried as a tracer. For these tests the Miran analyzer was set at a wavelength of 10.7 μm and a pathlength of 20.25 m.

The continuous electron capture detector (ECD) system, developed in Phase I, was also tried out in the field tests using SF_6 as a tracer. It was not used on a regular basis since the THC system worked so well and was easier and less time consuming to set-up and operate. The continuous ECD system consisted of a Varian 1400 gas chromatograph with an electron capture detector. Sample gas was pumped via a stainless steel bellows (Metal Bellows

ORI

Model MB 41), was rinsed with "zero" grade hydrogen, and was passed through a 3 mm O.D. stainless steel tube packed with Girdler 6-43 catalyst (platinum on gamma alumina) heated to 200°C. The resulting oxygen-free sample passed through two condensers, one maintained at 3°C by a U-cool refrigeration unit, the other maintained at approximately -15°C by a salt-ice bath. The sample gas then entered the ECD. This system is illustrated schematically in Figure 16. Output from the electrometer on the gas chromatograph was recorded using a Hewlett Packard Model 3155B chart recorder. The minimum detectable concentration of this system was approximately 0.1 ppb SF_6.

A sampling train as shown schematically in Figure 17 was used to conduct the sample from the exhaust duct to the gas analyzers. The continuous ECD system was teed into this sampling train when it was used. Tests on May 16, 17 and 18 were conducted using a straight probe, approximately 1.2 m in length, with perforations along its length, inserted in the rectangular section of exhaust duct at the same point at which velocity measurements were taken (Figure 18). In spite of the multiple openings in the probe a representative sample was not obtained because of stratification in the duct. Therefore a new probe system was designed and installed further downstream in the flexible duct as shown in Figures 17 and 19. Views of the whole analytical set-up are shown in Figures 20 and 21.

An AID (Analytical Instruments Development) portable gas chromatograph equipped with an electron capture detector was available on-site for SF_6 measurements and was used for flow measurements on the forcing air system before it was installed on the TBM, though it was not used during the actual test program. This instrument uses a 1.5 metre x 3 mm OD stainless steel column packed with molecular seive 5A for separation of SF_6 from air. The minimum detection limit for this system is 0.02 ppb of SF_6. Output from the GC is recorded on a Hewlett Packard reporting integrator, with calibration obtained by serial dilution of 1% SF_6 in air in Tedlar (polyvinyl fluoride) gas sample bags.

The following gases, all supplied by Matheson, Whitby, Ontario were available for use as tracers:

- 1% sulphur hexafluoride in air.
- 1% sulphur hexafluoride, 55% helium, 44% nitrogen (simulating the density of methane).
- propane, chemically pure (> 99.0%).
- methane, ultra high purity (> 99.97%)
- sulphur hexafluoride, chemically pure (> 99.8%).

Tracer Injection

The major portion of the field program consisted of measurement of tracer pulses of propane. The propane was injected at various points at the TBM face and was measured in the exhaust duct by the THC analyzer and the Miran analyzer.

The propane injection system consisted of a 150 cc stainless steel pressure bomb. The bomb was connected to a cylinder of propane, equipped with a regulator which was set at 210 KPa. At the outlet end of the bomb was a pressure gauge and a 115 V AC electrically operated solenoid valve. To fill the bomb the inlet valve would be opened until the bomb pressure reached 210 KPa, then the inlet valve would be closed. The bomb would then be connected to an injection port on the TBM face. Each injection port consisted of a tube fitting tapped into the plexiglass shroud, to which the bomb could be readily attached. The solenoid valve was connected to a switched circuit. A utility light was connected to the same circuit and was located at the other end of the machine where the operators of the analytical equipment were stationed. When the switch was tripped to release the propane from the bomb, the utility light would also come one, signalling to the analysts to lower the pens on the chart recorder and to start the integrator in order to start recording the trace. In this way the injection could be synchronized with the analysis. The solenoid valve system allowed fast and consistent release of the tracer in each test. Illustrations of the injection bomb filling procedure are given as Figures 22 and 23.

Two larger sample bombs, one 500 cc and one 1500 cc were also available for use. The 150 cc bomb proved to provide sufficient tracer for analysis and was used for all the tests since it allowed faster release of its contents than the larger vessels.

In addition to the pulse injection tests, some tests were conducted with constant, continuous tracer flow. For these tests a limiting orifice was used. A solenoid valve was used to start and stop the flow and the utility light signalling system was connected to enable synchronization with the analysis.

A data sheet was filled out for each data point, with the date, time, trace identification number, sample injection point number, flow conditions, etc. Chart recorder and integrator traces were later cut up and taped to the appropriate data sheet. In this way the large volume of data collected could be readily organized, with all information for a given test condition being found on one sheet.

Smoke Bomb Tests

The video taping of the smoke bomb tests was done using a Hitachi Model FP40SU camera with a Fujinon A12 x 9 Model RM 6 lens. Because the face of the TBM was within 10 m of the wall of the building, a wide angle adapter had to be used in order to get most of the TBM face within the picture. The effective focal length of the camera was 4.5 mm with this adapter. A JVC Model CR 4400 U video recorder was used to record the tests on Scotch MBU 18s video tape.

Because the taping was conducted at night and plant lighting was not bright enough for videotaping, additional lighting was required. A lighting specialist was consulted. Two 10 KW lights and two 2 KW lights were used to illuminate the head, with two "space" lights within the head.

The smoke bombs were 45 second duration ground-type smoke pots in red, blue, yellow and green and were obtained from Hand Fireworks Inc. For some tests two smoke bombs were used in order to provide a denser smoke.

For each test, except the last, the smoke bombs were ignited and placed at the intake to the forcing air fan. The smoke was then pulled into the fan and filled the head. Videotaping was started just before the bomb was ignited and was stopped after the last traces of smoke had left the head.

For the last smoke test (#10), the bomb was ignited within the head with the forcing air off and was waved around to disperse the smoke as much as possible.

6. TEST PROGRAM

The test program as it was originally planned is outlined in Table 1. The original maximum value of 6 RPM was not attainable and was therefore dropped. The start of the program was delayed, however, because the support crew at the plant was not available for work until May 16, 1983. The actual test program is given in Table 2.

The smoke bomb tests were completed in one day, which was faster than expected. Ten of these tests were conducted under various forcing and exhaust air flows and various rotation speeds. All ten tests were recorded on colour videotape, from which two copies on videotape, two 16 mm films and one super 8 mm film were subsequently made. Table 3 lists the conditions for each smoke bomb test.

The tracer addition and analysis systems required some time for familiarization. Some of this preliminary work was carried out on May 16th. The sampling train was set-up and injections were made to determine whether an adequate response could be obtained using the 150 mL sample bomb with propane at 210 kPa, or whether one of the larger sample bombs or higher pressure would be required. The 150 mL bomb at 210 kPa was found to be sufficient.

Velocity profiles of the exhaust and supply ducts and further familiarization tests were carried out on May 17th. These tests involved trials to determine a protocol for injecting the tracer. Injections were made both when a blade was passing an injection point and when a space between two blades was passing the injection point. In order to minimize possible effects due to differences in injection, it was decided to inject all tracer pulses when the head was in the same position. One of the blades was, therefore, marked and the tracer was injected as this mark passed point #19 on the shroud face.

A test was performed to determine the lag time of the analysis set-up by inserting the sampling probe into the duct after a tracer had been injected and noting the time until a response was seen. Lag time for the Miran analyzer was 1 second and 4.5 seconds for the THC analyzer.

One extra parameter which was not included in the original test program was noted during these early tests. The head can rotate in a clockwise or counter-clockwise direction. Some tests were performed at point #9, injecting both on and between blades, for clockwise and counter-clockwise directions. The direction of rotation did have an effect on the observed tracer responses.

A total of 20 injection points were installed on the face, most placed symetrically, and others concentrated in areas that it was thought might cause problems.

A complete test series of all injection points at 0 RPM, 4.0 m^3/s forcing air, 7.08 m^3/s exhaust air was begun on May 17th and completed on

May 18th. This test was conducted with the head aligned so that the two forcing air ports were not equally open. The test was later repeated, on May 19th, with the head properly aligned and the forcing air ports equally open.

A test series at 4 RPM, with 4.0 m^3/s forcing air and 7.08 m^3/s exhaust, was begun on May 18th. The machine could not run for long at this speed, however, due to overheating. This overheating problem was not resolved during the course of the program and meant that tests at 4 RPM required several days to complete, with only a short time each day at 4 RPM.

In examining some of the traces obtained on May 18th, it was noticed that the area under the trace obtained at some points appeared to be much lower than others. Since the same amount of tracer was injected at each point, the trace areas should have been the same. The cause of this problem was found to be stratification in the exhaust duct. This was determined by injecting tracer into each of the four exhaust openings at the face and observing the traces.

For May 19th a new sample probe was constructed, consisting of four sample points arranged at the apexes of a square. This probe was placed further downstream in the exhaust duct, within the flexible ducting. The integrator was installed on the THC output at this time as well to measure the area of every trace. A test of the new probe system by injecting the same amount of tracer into each of the four exhaust openings, in turn, showed excellent agreement in the area of the response obtained, indicating that the stratification problem had been eliminated.

At this time two additional injection points were installed, points #21 and #22. A complete test series of all 22 points was then conducted, with the head aligned properly at 0 RPM, 4.0 m^3/s forcing air and 7.08 m^3/s exhaust air. A test series at 2 RPM counter-clockwise, with the same ventilation conditions, was begun on May 19th and completed on May 20th. A complete test series under the same conditions, but clockwise at 2 RPM, was also completed on May 20th.

On May 21st two test series at 2.3 m^3/s forcing air and 4.72 m^3/s exhaust air, at 0 and 2 RPM respectively, were conducted Some test points were studied using a continuous injection of methane and comparison tests of pulse injections of propane and methane were carried out at point #20.

In order to gain as much information as possible on a wide range of conditions, three test points were selected to examine more closely. These were points #2, #5 and #16. A matrix of ventilation flows vs rotation speeds of 0, 1, 2, 3 and 4 RPM was devised. These "matrix tests", as indicated in Table 2, were started on May 22nd and eventually completed on May 27th.

On May 23rd a complete test series was performed with no forcing air and 4.72 m^3/s exhaust at 2 RPM counter-clockwise. At that time a set of injections was carried out at point #16 and then point #2, with injections as blades other than the marked blade passed point #19.

The remainder of the test program involved completion of test series and the matrix tests, using pulsed injections, except for a set of continuous methane injections on May 26th. These were continuous injections into the forcing air, with measurement at specific points on the face.

Some attempts were made on May 27th to measure the volume of the head by injecting a known quantity of propane into the head, with no forcing or exhaust air, rotating the head to mix the propane, and then sampling the air in the head. These attempts were not successful, however, because good mixing could not be attained and concentrations as measured in the head varied greatly at different points.

In general the test program went extremely well. Data points were generated more quickly than even the most optimistic estimate of

5 minutes per data point. Depending on the ventilation conditions, data points usually required 2 to 3 minutes to complete. Problems with a noisy response from the THC analyzer were encountered on two occasions. However, the spare analyzer on hand was available and therefore downtime was minimized. Background hydrocarbon levels in the plant interfered with the THC response on two occasions. The first occurrence was due to natural gas fired heaters in the building. The source of the second occurrence was believed to be an acetylene tank. These interferences were controlled by opening the overhead doors in the plant to allow more ventilation and to prevent these gases from reaching levels that would interfere with the analysis. The overheating problem of the TBM caused delays throughout the program; however, the fast generation of data meant that the program could still be completed in the allotted time.

7. RESULTS AND DISCUSSION

7.1 Smoke Tests

The smoke bomb tests were very useful in illustrating visually the overall pattern of air movement within the head. After each test in the field the videotape was replayed in order to ensure that the test had been properly recorded. Subsequently, the videotapes were observed on a projection video system in order to see the traces with maximum clarity. In general, the tests using two smoke bombs gave better pictures than the tests using single bombs because of the density of the smoke produced.

The best demonstration of the ventilation system's ability to clear the head occurred as the smoke bomb finished. The head clears essentially from top to bottom and in the direction of rotation of the head. Thus, for clockwise rotation, the lower left quadrant is the last area to clear and the lower right is the last to clear for anti-clockwise rotation.

While the overall effect of the ventilation system is readily seen in the videotapes, finer detail of air currents within particular areas is more difficult to see. This is mainly due to the large face area that was necessary to include in the picture. More detail might be observed in a slow motion or stop frame analysis of the videotape.

7.2 Tracer Gas Comparisons, Methodology Comparison

Several of the tests conducted in the program serve to illustrate the suitability of the pulse propane injection technique for ventilation analysis on the TBM. These include tests using other tracers, SF_6 and methane, and tests using the continuous injection procedure rather than pulse injection.

On May 17 a few injections were performed using SF_6 alone and SF_6 in propane. The curves obtained for SF_6 on the continuous ECD system were very similar to those obtained for propane at the same point. Figure 24 shows the traces obtained for the THC analyzer and for the ECD analyzer for an injection of a mixture of 30 cc of 1% SF_6, 55% helium, 44% nitrogen, in the 150 mL bomb pressurized to 210 kPa with propane. In the figure the traces have been adjusted so that each is on the same scale. As can be seen, the traces are nearly identical. The lag time of the ECD was longer than the THC; however both have sufficiently fast rise and fall times to adequately represent the pulse trace.

Figure 25 shows a comparison of methane and propane injections at the same test point for the same conditions. For the methane test, the 150 cc bomb was filled to a pressure of 210 kPa, as in the propane tests. The actual response for methane is approximately 3X lower than for propane, but when the traces are corrected for this factor, similar shapes are observed.

Propane was chosen over methane as a tracer for detection using the THC analyzer because three times the response can be obtained for the same quantity injected. Since it is only necessary to inject a relatively small volume, the injection can occur in a very short time period, a distinct advantage for the short time intervals involved in this particular ventilation system. The possible problem with using propane to simulate the removal of methane from the head area is the difference in density between methane and propane. Methane will rise in air, whereas propane will sink, since it is denser than air. As can be seen in Figure 25, no difference can be seen between methane and propane injections, indicating that no buoyancy effect is observed. This is due to the fast air movement in the head. Methane and propane would not have sufficient time to rise or sink to any significant extent because of the fast air movement and mixing in the head area.

Many tracer studies are carried out using continuous flow of a tracer and observation of the decay in concentration of the tracer after the tracer is stopped. Continuous injections of methane at various points on the face were performed on May 21. The time to detection, time to maximum concentration, value of maximum concentration, and time for removal can be obtained from these traces. The same type of information can also be obtained from pulse injections and the continuous injections do not provide any additional information which cannot be obtained from the pulses, but each continuous test takes much longer to complete. The pulse technique, therefore, can be justified as being a more effective procedure for this type of study.

Some tests were carried out using continuous injection of tracer into the forcing air, with measurement at the TBM face. These approach the problem of determining methane removal from another point of view. The times to observation of a response indicate the time it takes the forcing air to reach a given point. If one of the sampling points is not well ventilated,this time, the decay portion of the curve, should be a strong indication. A comparison of the data obtained from these curves (Table 4) with data from the pulse technique, discussed below, indicates that no significant advantage is obtained with continuous injection into the forcing air.

A comparison of the three tracer injection techniques shows that similar results are obtained, even though the techniques are quite different. The fact that these methods reach the same conclusion serves to strengthen the confidence in the results obtained.

7.3 Pulsed Tracer Injection Results

The major portion of the field program involved pulse injections of propane. Several hundred injections were performed under varying conditions. The resulting traces for each of these has been compiled as a separate appendix. The traces obtained have been scaled down and re-drawn in Figures 26 to 47 for the 22 injection points on the face and in Figures 48 to 50 for the three points in the "matrix" tests.

The traces on each page are arranged by ventilation condition and by rotation. Some trends in peak shape, peak height, number of peaks, etc., can be observed in these figures. The changes in scales both for time and concentration should be noted when comparing traces.

For zero rotation and maximum ventilation conditions, injections at most points on the face resulted in single sharp peaks (top right corner of each of Figures 26 to 47). At zero rotation, and lower ventilation flows, peak shapes tended to be less regular and multiple peaks were obtained at some points (e.g. point 3, 9, 10, 15, 18, 20, 22). With higher rotations the same general trend is observed, peaks being more irregular with increased rotation. The two effects seem to combine and, at 4 RPM with low flow, numerous peaks are observed for most points. These peaks occurred in a regular pattern at intervals corresponding to 1 revolution (every 30 seconds at 2 RPM, every 15 seconds at 4 RPM).

The same general trends in peak shape are shown more clearly for the matrix tests at points 2, 5 and 16. Peaks are very sharp at high air flowrates and low rotation, but tend to spread and to become multiple peaks with lower air flowrates and fast rotation.

8. DATA ASSESSMENT

The primary objective of this study was to assess the efficiency of the head ventilation system to remove methane gas leaking from the face into the TBM. To make any such assessment it is necessary to extract information from the tracer gas concentration versus time curves, illustrated and discussed in the previous section and present it in graphical or tabular form. Several approaches, some of which have been utilized successfully in other tracer gas studies(1-3), are used below to illustrate relative ventilation efficiency. Where possible the effects of parameters such as forcing and exhaust air flowrates, head rotational speed and direction, tracer gas addition location and internal head structure on ventilation efficiency are noted. An attempt is also made to account for the varied shapes of tracer gas concentration versus time curves for the different TBM operating conditions.

8.1 Tracer Gas Removal Efficiencies

Curves indicating the percentage of tracer gas removed from the head with time, for 20 addition points on the shroud face, are given in Figure 51. Each curve was obtained by measuring the area under the gas concentration trace for a given time interval, dividing by the total area under the trace, and then plotting these values as percentages of tracer gas added against time. Areas were carefully measured with a planimeter. Test conditions for this set of curves were maximum forcing and exhaust air flowrates of 4.0 m^3/s and 7.08 m^3/s respectively and no head rotation.

The figure shows that for all addition points tracer gas is first detected at the sampling location within 8 - 11 seconds after injection. It had previously been determined by introducing tracer gas directly at the exhaust air vents that the lag time before tracer gas detection by the analyzer was 4.5 seconds. Time taken for the tracer gas therefore to pass from the shroud injection point to the exhaust air vents is in the range of 3 - 6 seconds for all points on the face. It is apparent, therefore, that the tracer gas was not injected into a stagnant air region of any significance at the shroud face.

It is also apparent that for all addition points virtually all of the added tracer gas is removed within one minute after injection. However, the rate at which the tracer is removed over that time varies considerably from point to point. This is illustrated in Table 5 where the time for 80 percent removal of tracer is given for each addition point, as well as the percentage removed after 20 seconds. At points 11, 18 and 12, for example, it takes twice as long to remove 80% of the tracer gas than it does at points 15, 3 and 4, and 20 seconds after tracer injection the percentage of gas removed varies from 90 percent at point 15 to 33 percent at point 12.

It is noted by reference to Appendix A that all the points for which the tracer gas removal rate is relatively fast lie on the central vertical axis of the face below the forcing air inlet ports, or lie within an inner circle defined by the inner spaces between blades or by the "muck ring". All points for which the tracer gas removal rate is relatively slow, apart from point 12, lie outside an outer circle defined by the ventilation holes in the back of the head. This might be expected due to the positions of forcing air and exhaust air vents relative to these points on the face. However, the internal structure of the head seems to have a significant impact on air flow patterns within the head since tracer gas removal rates are not always similar for equivalent locations on either side of the central vertical axis. The effects of internal head structure are discussed further in subsequent sections of the report.

When the forcing and exhaust air flows are reduced, the tracer gas removal rate also decreases, as seen in Figure 52 for points 3 and 14. However, the rate reduction is significantly greater for point 14 than for point 3. Table 6 illustrates the magnitude of the changes occurring for three separate flow conditions. Comparing the times required to effect 80 percent removal of tracer gas going from maximum to minimum air flow, it is seen that t (secs) increases by a factor of 2.4 for point 3 and 4.1 for point 14. Perhaps the most notable effect in reducing air flow when injecting tracer gas at point 14 is the greatly increased time interval before any tracer is detected at the sampling point in the exhaust duct (Figure 52). This is obviously a result of point 14 being at a location furthest from the exhaust vents with no forcing air and minimum exhaust flow. The air movement around the outside edge of the face is slow and hence the effects noted for point 14 are also true for other outside locations such as 9, 10, 11, 13, 18, 20 and 21.

With respect to methane leakage, at a rate less than 0.1 m^3/s, at any point into the head when operating the TBM underground, it appears unlikely, based on an assessment of this data, that there could be a significant build-up of methane within the head to reach hazardous levels when the exhaust flowrate is 4.72 m^3/s or greater with some forcing air. However with no head rotation, no forcing air and a minimum exhaust air flow of 2.3 m^3/s, methane leakage at the outside edge of the head might be a problem if frictional ignition were to occur at that location.

8.2 Effect of Parameters on Tracer Removal and Trace Shape

While the above evaluation of the percent removal of tracer with time is the most appropriate way of analyzing the data with respect to the objective of determining the ability of the ventilation system to remove methane from the head, other ways of analyzing the data may be more helpful to further characterize and describe ventilation patterns.

Figures 53 to 59 are isopleth drawings generated from the maximum concentrations observed from injection at various points on the face, for a variety of test conditions. These drawings should be interpreted with some caution since the procedure of developing the isopleths can be subject to some distortion by some peaks that are significantly different from the rest. Also, the parameter of maximum concentration may not always reflect ventilation efficiency, especially where there are irregular or multiple peaks. Percent removal at a given time, or time to a given percentage removal might be better parameters for analysis, but the generation of these values requires an extensive time-consuming effort if done manually and would only be worthwhile if the data were digitized and analyzed by computer. The selection of maximum concentration for these isopleths was chosen because it could be obtained directly from the data sheets.

The effects of rotation, ventilation flows, and head structure can be demonstrated using these diagrams. At zero RPM, Figures 53 and 56 show that the ventilation pattern is not regular or symmetrical, especially at the lower ventilation condition. The increased irregularity at low flow may be to some extent a reflection of the more irregular peak shapes under those conditions. Both isopleth drawings at 0 RPM show better ventilation along the top to bottom axis and a tendency toward the best efficiency being at the centre. It is somewhat surprising that the region to the left and below centre has such a high concentration in both situations. This may be a function of the particular head position during injection, with some aspect of the head structure affecting the results.

With rotation at 2 RPM (Figures 54, 57 and 58) a skewed effect in the direction of rotation is observed. This is particularly evident in the two plots at 4.0 m^3/s forcing air and 7.08 m^3/s exhaust air, for clockwise and counter-clockwise rotations.

At 4 RPM the same skewed effect is evident for 2.3 m^3/s forcing air and 4.72 m^3/s exhaust air, but at 4.0 m^3/s and 7.08 m^3/s the pattern is very symmetrical.

A series of tests made at point #2 relates trace shape with injection time and head structure. Tracer was injected at point #2 for

16 different positions of the rotating head as each of the 16 blades passed point 19 on the shroud face. The marked blade was identified as Blade A for the purposes of this test and the other blades were identified alphabetically in a clockwise direction. It was found that for injection at several of these blades, the peak shape was significantly different. The peak shape changed in a regular pattern related to the different blades in the head. Four distinct patterns were observed.

These different shape traces are related in some way to four different possible head positions at the time of injection. This is demonstrated in Figure 60 which shows the position of the forcing air ports and corresponding holes in the TBM head, with the tracer observed when the head is in those positions. The relationship of the trace shape may not be directly related to the forcing air duct positions, but could be related to some other aspect of the head structure which also has four distinct positions.

The same type of test series, when injecting tracer at point 16, did not reveal peak shapes different than that for the normal injection position of Blade A. It is possible though that points other than point 2 may show the same dependency of injection position.

The above results indicate that the body of data for all points obtained with injection of the marked blade (Blade A) passing point 19 should be interpreted in light of the fact that, at different injection positions, different peak shapes and therefore different maximum concentrations might be observed. This might effect the isopleth drawings for example. However, the observed differences in peak shapes would not significantly effect removal efficiency data based on the time to remove 80% or 90% of the tracer.

8.3 Mathematical Analysis of Tracer Gas Concentration Versus Time Curves

Simple and complex mathematical equations have been developed to account for the rate of change of tracer gas in a ventilated space. Some of the mathematical models are reviewed in the report on Phase 1 of this study. If it is assumed that no tracer gas exists in the ventilation air, that no tracer is generated or absorbed within the space and that perfect mixing of tracer occurs, then the rate of change of tracer can be expressed by the simple relationship

$$\frac{dc}{dt} = - \frac{\gamma}{v} c$$

which may be solved to give

$$\ell n \frac{c}{c_0} = - \frac{\gamma}{v} t$$

where c is the concentration of tracer at time t, c_0 is the initial tracer concentration, v is the volume of ventilated space and γ is the rate at which air is removed from, or enters, the ventilated space in volume per unit time. If $\ell n\ c/c_0$ is plotted against lapsed time, therefore, the slope of the line is equal to - γ/v, representing air changes per unit time.

In many other studies where tracer gas decay is followed over a long time period, the tracer is added at a fixed rate, until a maximum concentration is attained at the sampling location and then cut-off. This maximum concentration is therefore the initial concentration c_0. When tracer gas is added as a pulse, as in this study, then at the sampling location the tracer concentration rapidly increases to a maximum value, with subsequent decay with time. This maximum, c_0, is taken to be the initial concentration at time t = 0. If perfect mixing occurs both initially and throughout the period of measurement, then a plot of $\ell n\ c/c_0$ against lapsed time should give a straight line whose slope is equal to the exchange rate of air within the space over that time.

In actual practice perfect mixing rarely occurs and the exchange rate equation may be written as

$$\ell n \frac{c}{c_0} = -k \frac{Y}{V} . t$$

where k is some constant allowing for imperfect mixing, though poor mixing generally destroys the simple logarithmic decay rate. A comparison of concentration versus time relationships for four simple models ranging from perfect mixing to non-mixing is given in Figure 61(3).

In order to obtain a meaningful plot from a tracer decay curve, especially when it occurs over a very short time period, it is preferable to have a single peak with minimal distortion of the decay to a readily identifiable baseline. In this study it has been shown that a number of parameters such as head rotational speed and direction and internal head structure may greatly effect the shape of the tracer gas concentration curve. Out of the several hundred tracer gas tests performed during this study, relatively few tracer concentration-time curves were a single peak with an apparent exponential decay. However, in order to illustrate the gas concentration versus time relationships, a number of plots were made and some are presented in Figures 62 - 64.

In Figure 62 plots are presented for addition points 2 and 11 at differing ventilation conditions. For point 2 with maximum forcing and exhaust air flows there is a distinct change in slope such that two straight lines can be drawn. It has been suggested(1) that a change in slope will occur if eddy zones are present in the ventilated spaces. These zones are regions of poor ventilation where tracer gas is not well mixed with dilution air. However, for point 11 with intermediate forcing and exhaust air flows, the plot shows a downward curvature whose slope is continuously increasing and it is not possible to draw a straight line. This concentration versus time relationship is reported to be representative of non-mixing.

Figure 63 shows similar downward curves for addition point 18 at both maximum and minimum air flows evaluated, though perhaps a straight line could be drawn through most of the points for the maximum air flow condition. In Figure 64 straight line plots are made for addition points 17 and 19 at minimum flow conditions with no forcing air. For these tests the head was rotating at 4 revolutions per minute and the tracer gas concentration versus time curves showed multiple peaks with concentrations apparently decreasing in exponential fashion. The straight line plots in Figure 64 were, therefore, obtained by plotting peak concentrations versus time.

As mentioned previously in this report, once the tracer gas enters the head, it is subjected to varying air flowrates and directional patterns in passing through the head to the exhaust duct, due to the internal head structure which can restrict air movement. The tracer gas decay plots referred to above are not similar and illustrate the difficulty in attempting a mathematical interpretation of the data. It is possible that computer techniques could be used to effect a meaningful mathematical analysis and interpretation of all the test data.

If the volume of the head and ducting to the gas sampling location is estimated to be approximately 50 cubic metres, then for perfect mixing and uniform air distribution and flow velocity within this volume, the slope of the tracer gas decay plot should be equal to - $\gamma/50$. For exhaust flowrates of 7.08 m^3/s, 4.72 m^3/s and 2.3 m^3/sec, the slopes should therefore be - 0.142, - 0.094 and - 0.047 respectively. Slopes calculated for the lines obtained in Figures 62 and 64 are - 0.26 (corresponding to - 0.142) and - 0.074 and - 0.061 (corresponding to - 0.047). Assuming that the estimated volume is reasonably accurate, the deviation of slopes from predicted values must be due to the effects of forcing air, head structure and rotation.

9. CONCLUSIONS

Major conclusions drawn from the information and data collected from head ventilation assessment tests during the TBM shop floor trials are as follows:

- The TBM ventilation system removes gas leaking into the head fairly rapidly through exhaust ducts under most available ventilation conditions and for all locations across the head face.
- The rate of gas removal from within the head varies with the location of gas leakage at the head face.
- Gas removal is slowest when there is no forcing air, minimum exhaust air and gas leakage occurs at the edge of the head face.
- The shapes of tracer concentration versus time curves are dependent upon location of tracer addition point, position of cutter head blades at the moment of gas addition, head rotational speed and direction, forcing air and exhaust air flowrates and internal head structure.
- Though the effects of specific parameters, such as head rotational speed, on traces are clearly identified for tests in which all other conditions remained constant, parameter effects are clearly interdependent. This precludes a definitive explanation of most traces which would require extensive analysis using computer techniques.

- Simple mathematical models do not appear to account for tracer gas decay plots obtained from this test program.

- Tracer gas techniques as applied in this study provide an effective approach for assessment of the TBM head ventilation system.

- Tracer gas addition, sampling and analytical methods selected for this study proved to be reliable, reproducible and appropriate and were justified on the basis of the data obtained.

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TABLE 1

Original Test Program

Date	
May 13-15	Smoke bomb tests with colour videotaping; tracer gas familiarization.
May 16-20	Tracer gas tests at 4.72 m^3/s forcing air, 7.08 m^3/s extracting air at various rotational speeds (0, 2, 4, 6 RPM).
May 21-23	Tracer gas tests at 2.3 m^3/s forcing air, 4.72 m^3/s extracting air at various rotational speeds (0, 2, 4, 6 RPM).
May 24-26	Tracer gas tests of reduced flow extraction only (2.3 m^3/s) at various rotation speeds (0, 2, 4, 6 RPM).
May 27-28	Tracer gas tests at 2.3 m^3/s and 4.72 m^3/s forcing air only, with head stationary.

TABLE 2

Actual Test Program

Date		
May 16	●	Smoke bomb tests
	●	Familiarization
May 17	●	Familiarization
	●	Flow measurement
	●	Injection tests before, on and after blades
	●	Lag time determinations
	●	Stationary head (not aligned) 4.0 m^3/s F.A., 7.08 m^3/s E.A.
May 18	●	4 RPM cc, 4.0 m^3/s F.A., 7.08 m^3/s E.A.
	●	Injection before and after blades
May 19	●	Stratification test
	●	0 RPM, 4.0 m^3/s F.A., 7.08 m^3/s E.A., head aligned
	●	2 RPM cc, 4.0 m^3/s F.A., 7.08 m^3/s E.A.
May 20	●	2 RPM cc, 4.0 m^3/s F.A., 7.08 m^3/s E.A. (completed)
	●	4 RPM cc, 4.0 m^3/s F.A., 7.08 m^3/s E.A. (continued)
	●	2 RPM c, 4.0 m^3/s F.A., 7.08 m^3/s E.A.
May 21	●	4 RPM cc, 4.0 m^3/s F.A., 7.08 m^3/s E.A. (completed)
	●	0 RPM, 2.3 m^3/s F.A., 4.72 m^3/s E.A.
	●	2 RPM cc, 2.3 m^3/s F.A., 4.72 m^3/s E.A.
	●	Continuous methane flow at selected points, 0 RPM, 2.3 m^3/s F.A., 4.72 m^3/s E.A., and 0 m^3/s F.A., 4.72 m^3/s E.A.
May 22	●	Matrix tests (points #2, #5, and #16): 2.3 m^3/s F.A., 4.72 m^3/s E.A. at 0, 1, 2, 3, 4 RPM cc 2.3 m^3/s F.A., 7.08 m^3/s E.A. at 0, 1, 2, 3, 4 RPM cc 4.0 m^3/s F.A., 4.72 m^3/s E.A. at 0, 1, 2 RPM cc

.../cont'd.

TABLE 2 - Actual Test Program (cont'd.)

Date	
May 23	• 2 RPM cc, 0 m^3/s F.A., 4.72 m^3/s E.A.
	• Injection at each blade for point #2, for some blades at point #16
May 24	• 0 RPM, 0 m^3/s F.A., 2.3 m^3/s E.A. (partial set of points)
	• 4 RPM c, 0 m^3/sec F.A., 2.3 m^3/s E.A. (partial set of points)
	• 2 RPM cc, 0 m^3/sec F.A., 2.3 m^3/s E.A. (partial set of points)
May 25	• 4 RPM cc, 2.3 m^3/s F.A., 4.72 m^3/s E.A.
	• 4 RPM c, 2.3 m^3/s F.A., 4.72 m^3/s E.A. (partial set)
May 26	• "Matrix" tests (points #2, #5 and #16): 4.0 m^3/s F.A., 7.08 m^3/s E.A. at 3, 4 RPM cc 4.0 m^3/s F.A., 4.72 m^3/s E.A. at 3, 4 RPM cc 0 m^3/s F.A., 4.72 m^3/s E.A. at 1, 2, 3, 4 RPM cc 0 m^3/s F.A., 3.3 m^3/s E.A. at 4 RPM cc
	• Continuous injections into forcing air with measurement at face for selected points
May 27	• "Matrix" tests (points #2, #5 and #16) 0 m^3/s F.A., 3.3 m^3/s E.A. at 1, 2, 3 RPM cc 0 m^3/s F.A., 5.9 m^3/s E.A. at 1, 2, 3, 4 RPM cc

TABLE 3

Smoke Bomb Test Conditions

Test No.	Smoke Colour & No. of Bombs	Forcing Air m^3/s	Extraction Air m^3/s	RPM	Direction
1	green (1)	7.08	4.0	4	Clockwise
2	red (1)	7.08	4.0	4	Counter-clockwise
3	blue (1)	7.08	4.0	0	-
4	yellow (2)	7.08	4.0	2	Clockwise
5	blue (2)	7.08	4.0	4	Counter-clockwise
6	yellow (1)	4.72	2.3	4	Counter-clockwise
7	yellow (1)	4.72	2.3	2	Counter-clockwise
8	red (2)	4.72	2.3	0	-
9	green (1) and blue (1)	shut off at end of bomb	2.3	0	-
10	red (1) (in head)	0	2.3	0	-

TABLE 4

Comparison of Tracer Injection Methods

Injection Method	Point	F.A.	M.A.	RPM	Time to Detection	Decay Curve Slope
Continuous Methane in F.A.	20	2.3	4.72	2cc	13	-0.022
Propane Pulse	20	2.3	4.72	2cc	10	-0.023
Continuous Methane at Face	16	2.83	5.18	2cc	13	-0.026
Propane Pulse	16	2.3	4.72	2cc	9	-0.022

TABLE 5

Ranking of Tracer Gas Addition Locations
Based on Removal Efficiencies

80% Removal		After 20 secs.	
Addition Point No.	t(secs.)	Addition Point No.	%
15	16	15	90
3	16	3	89.5
4	18	4	85
2	19.5	2	81.5
6	21	6	75.5
7	22.2	7	72.5
8	22.7	8	69
20	23	20	67
9	23.7	9	65
16	24.2	16	64.5
5	24.7	5	61.5
1	25.2	1	58.5
19	26.0	17	53.5
17	26.2	19	47
10	27	14	45.5
13	28	13	44
14	29.2	10	40
11	30	18	37.5
18	33.2	11	34
12	34.5	12	33.5

TABLE 6

Effects of TBM Ventilation Conditions on Tracer Gas Removal Efficiency

80% Removal		After 20 secs.	
Position	t(secs)	Position	%
3(1)	16	3(1)	90
3(2)	20.3	3(2)	78
14(1)	28.2	14(1)	45
14(2)	38.4	14(2)	24
3(3)	42.5	3(3)	15
14(3)	116.4	14(3)	0

		(1)	(2)	(3)
Ventilation Conditions (no head rotation)	Forcing Air (m^3/s)	4.0	2.3	0
	Exhaust Air (m^3/s)	7.08	4.72	2.3

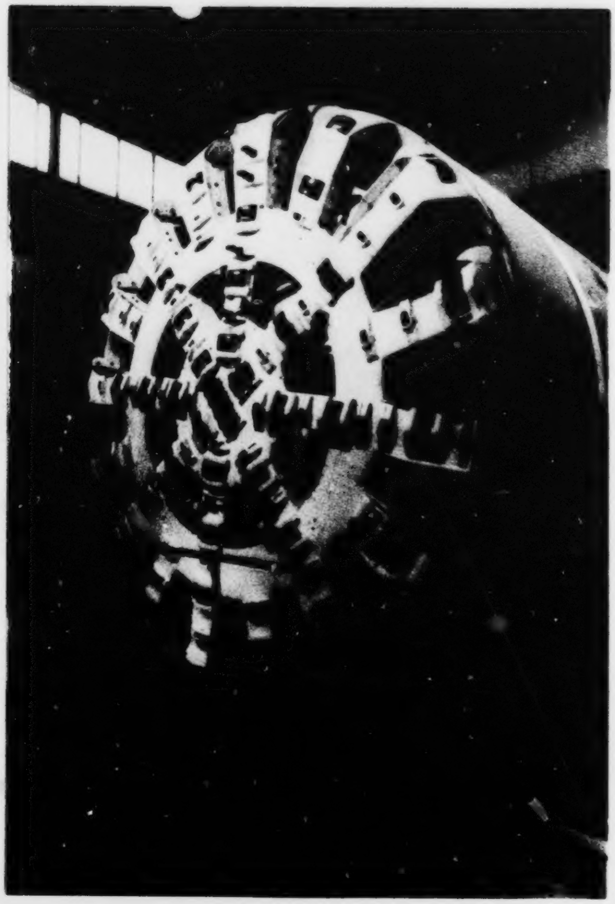


FIGURE 1 - Front-Side View of TBM

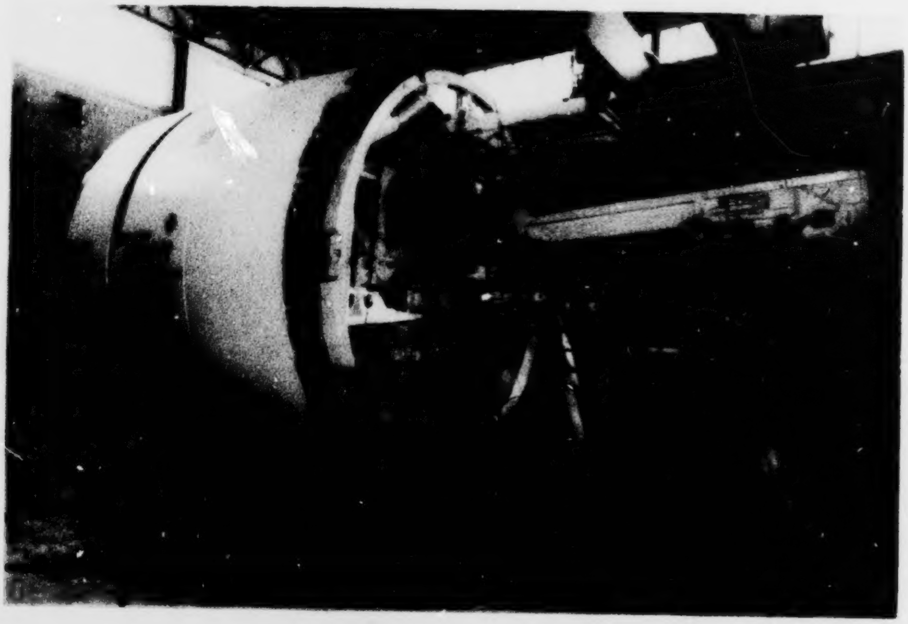


FIGURE 2 - Rear-Side View of TBM

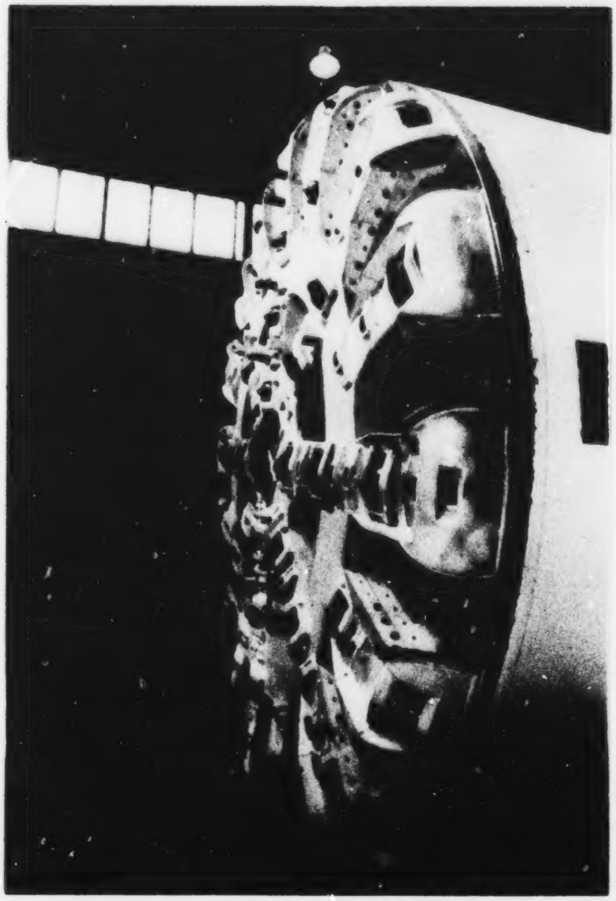


FIGURE 3 - TBM Cutter Head

FIGURE 4 - Rear View of TBM and Ancilliary Equipment

FIGURE 5

TBM Operating Controls

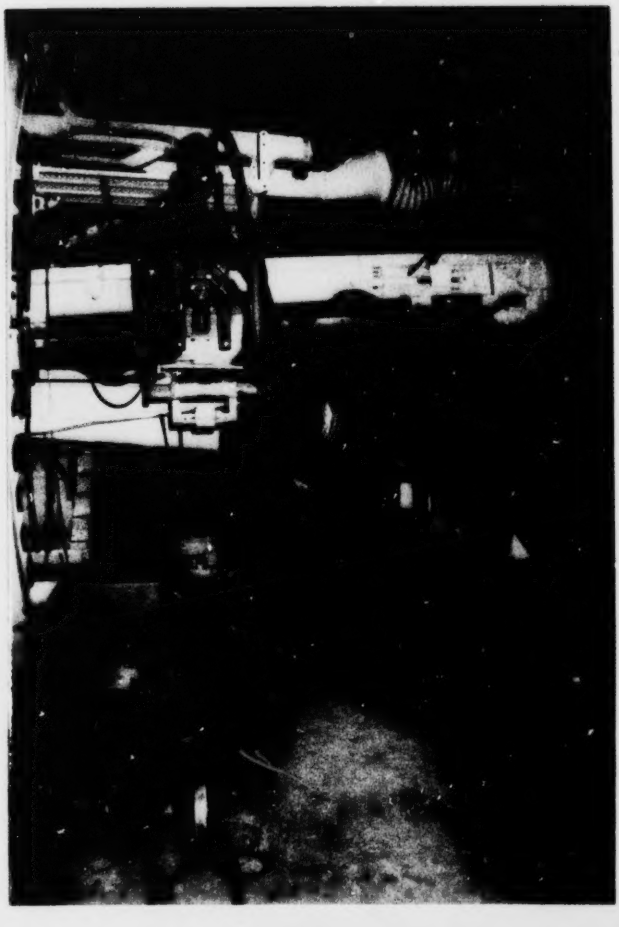
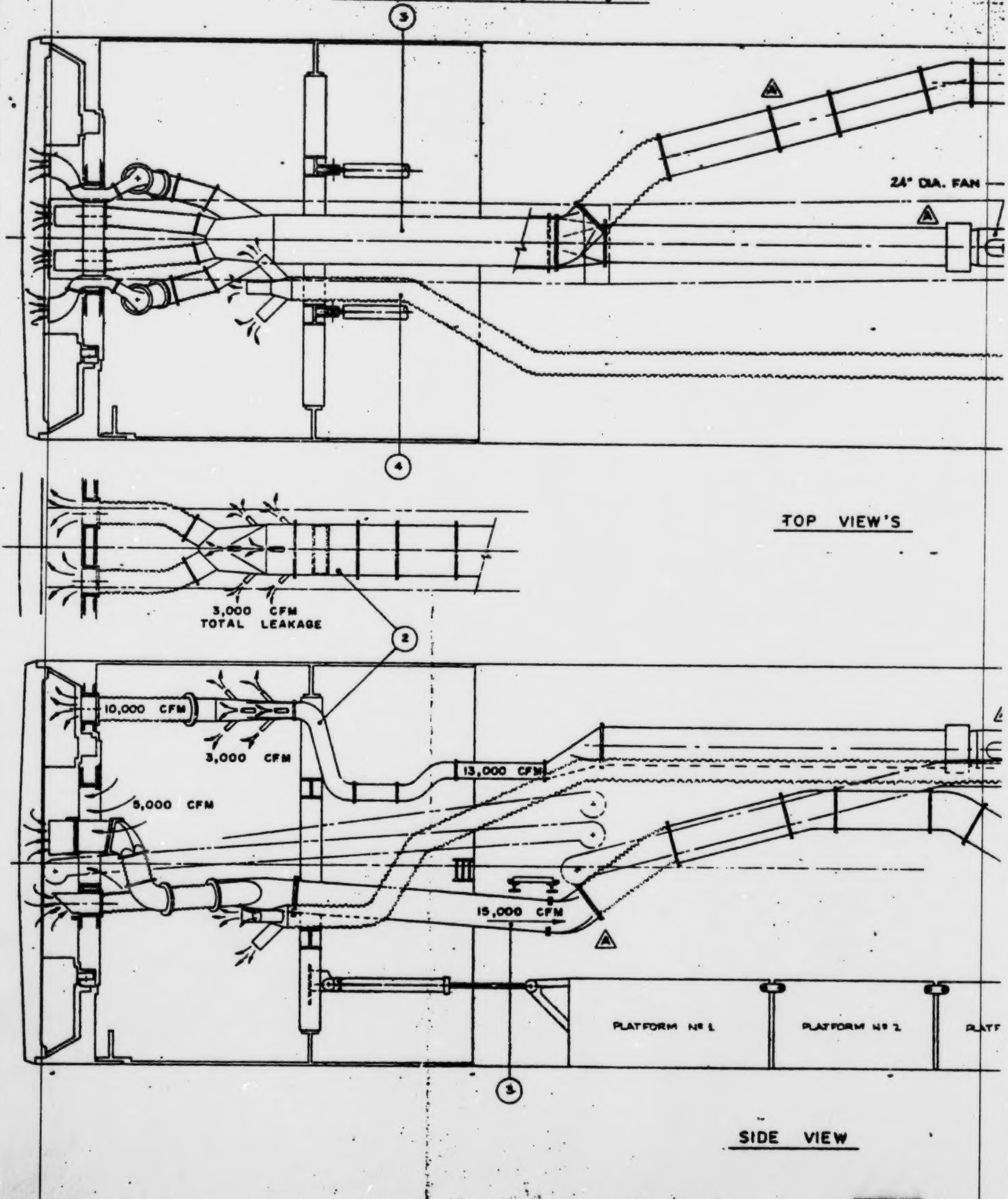


FIGURE 7

Forcing Air Fan Location

FIGURE 6

Head Ventilation System Layout


⑤
24" DIA. FAN
TOP VIEW'S
3,000 CFM
TOTAL LEAKAGE
②
④
10,000 CFM
3,000 CFM
5,000 CFM
13,000 CFM
15,000 CFM
PLATFORM No 1
PLATFORM No 2
PLATF
③
SIDE VIEW

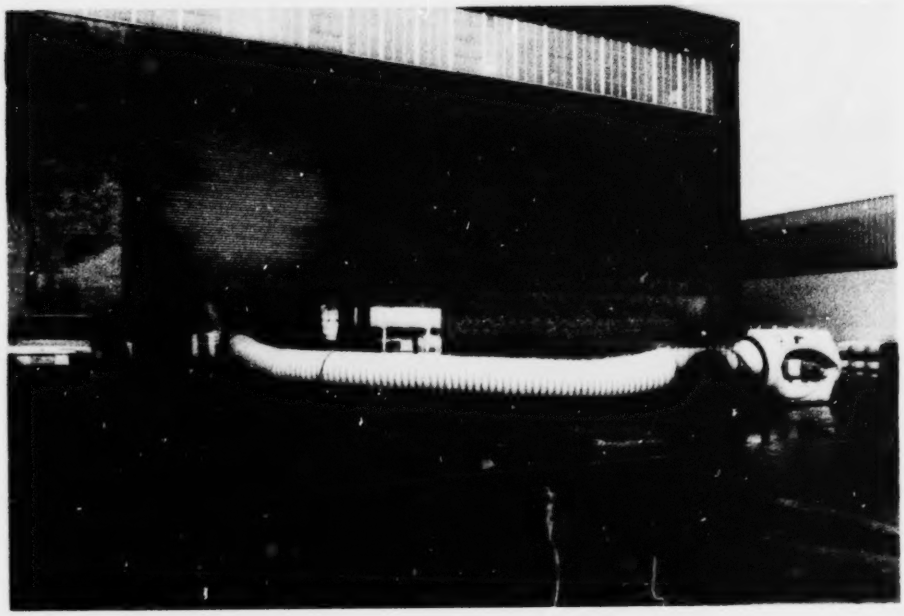
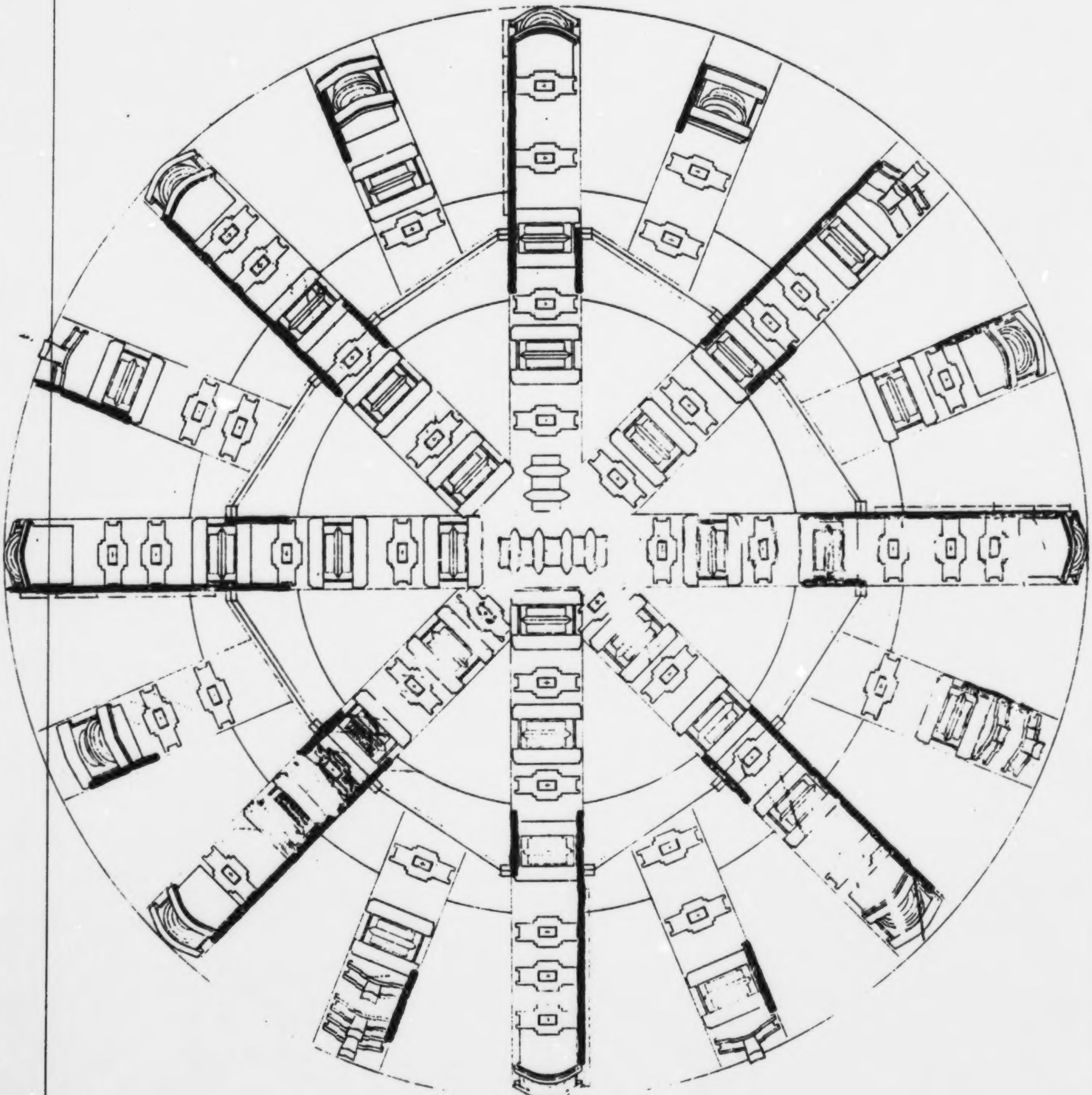


FIGURE 8

Exhaust Air Duct and Fan

FIGURE 9

Cutter Head Blade Arrangement



Dia. = 7.6 m

FIGURE 10

Blade Space Pattern

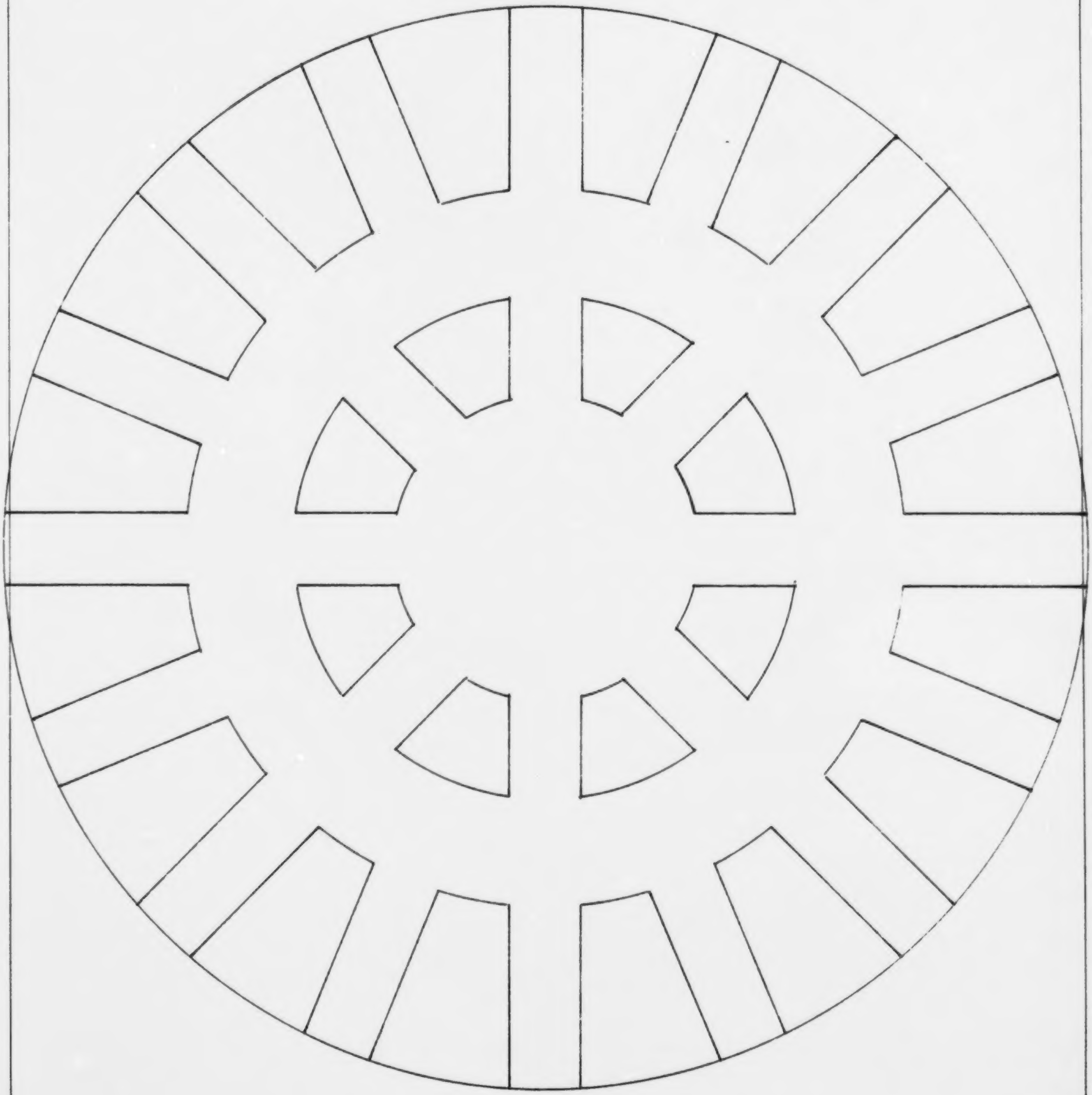


FIGURE 11

Head Back Plate Ventilation Holes

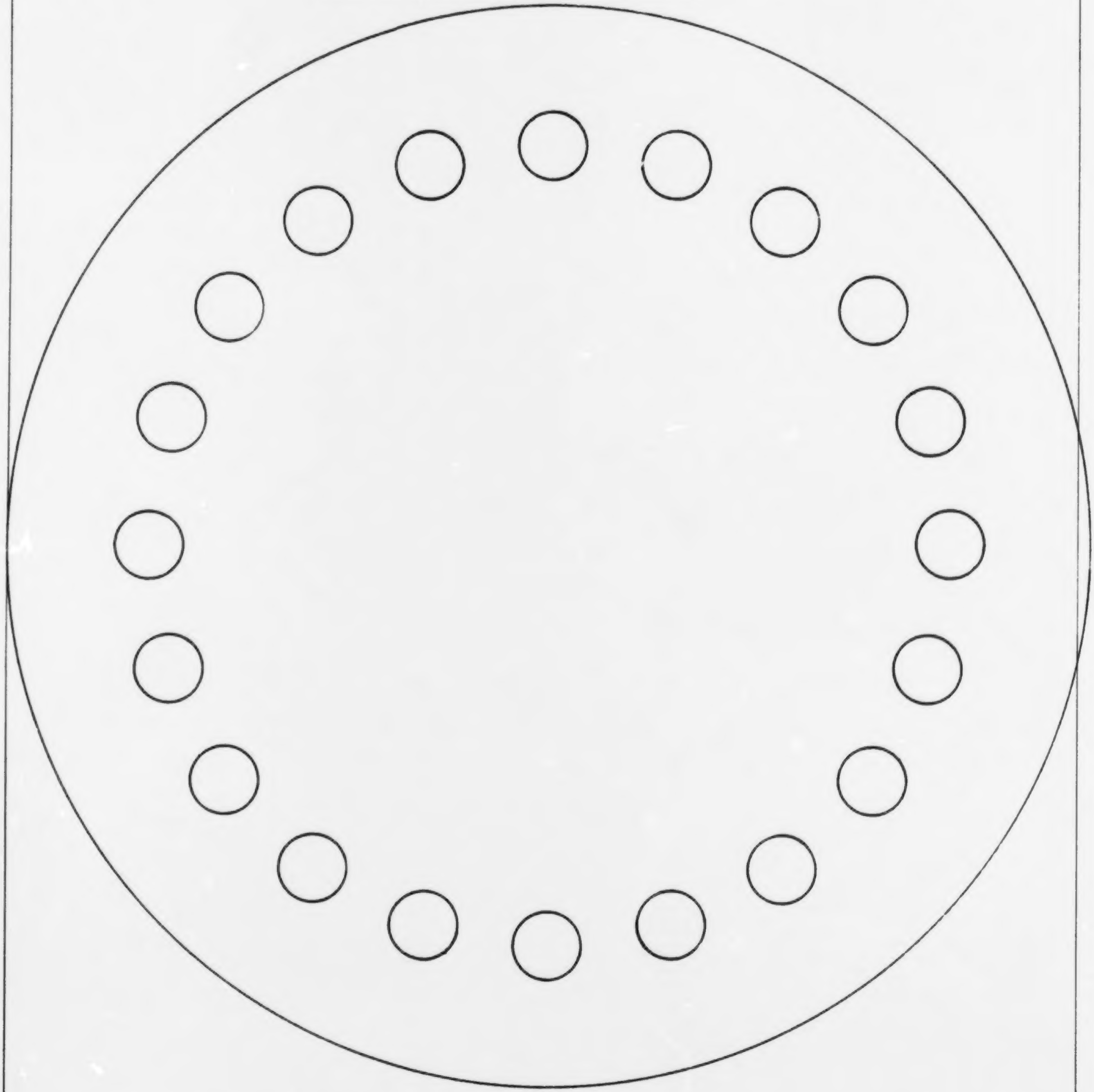
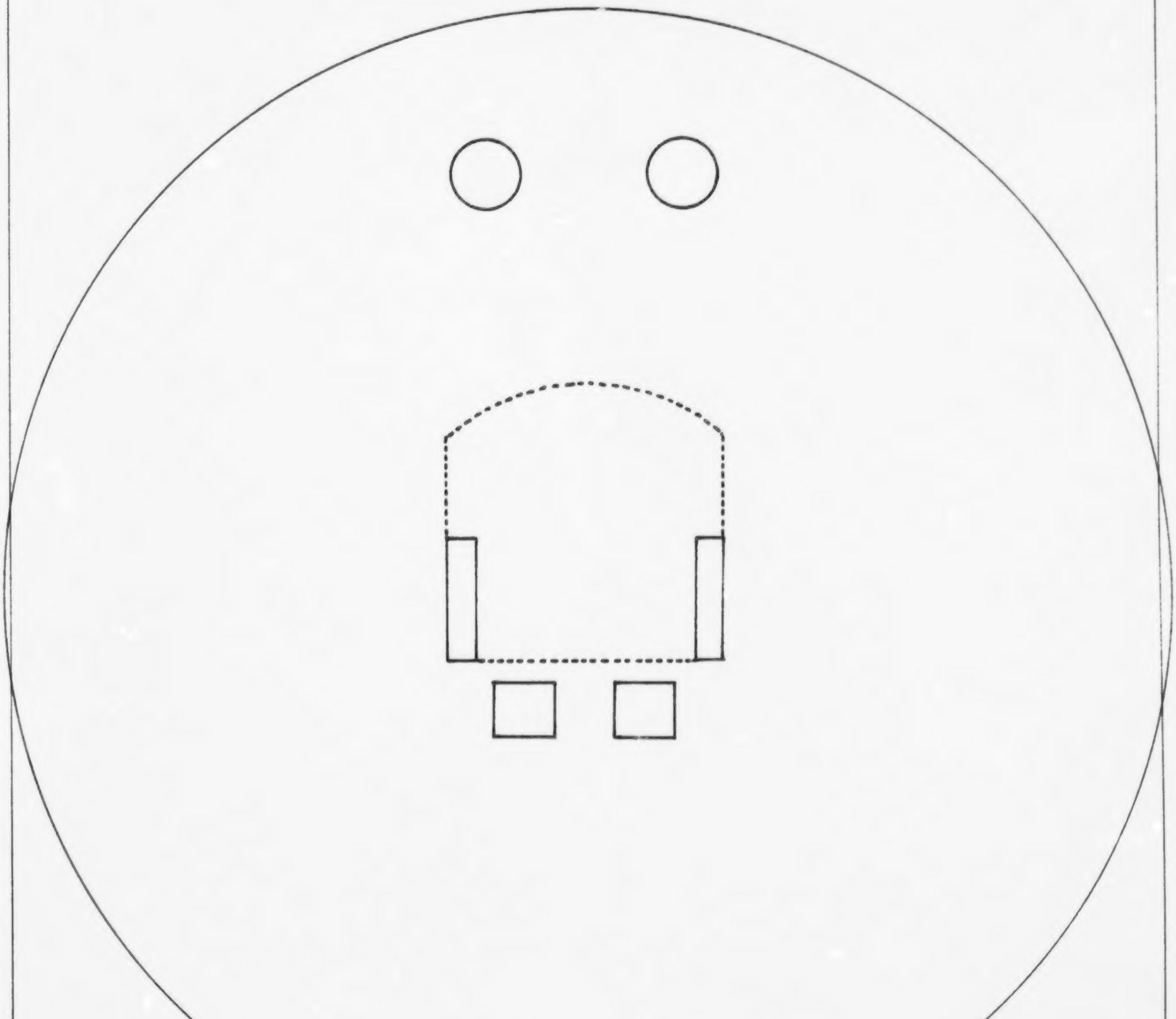


FIGURE 12

Forcing and Exhaust Air Vents



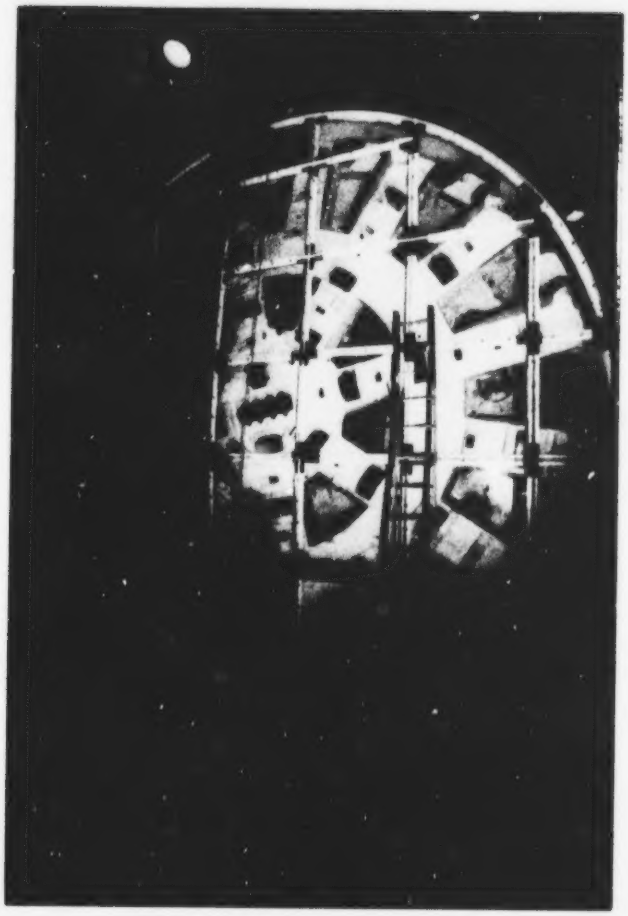


FIGURE 13

Head Shroud

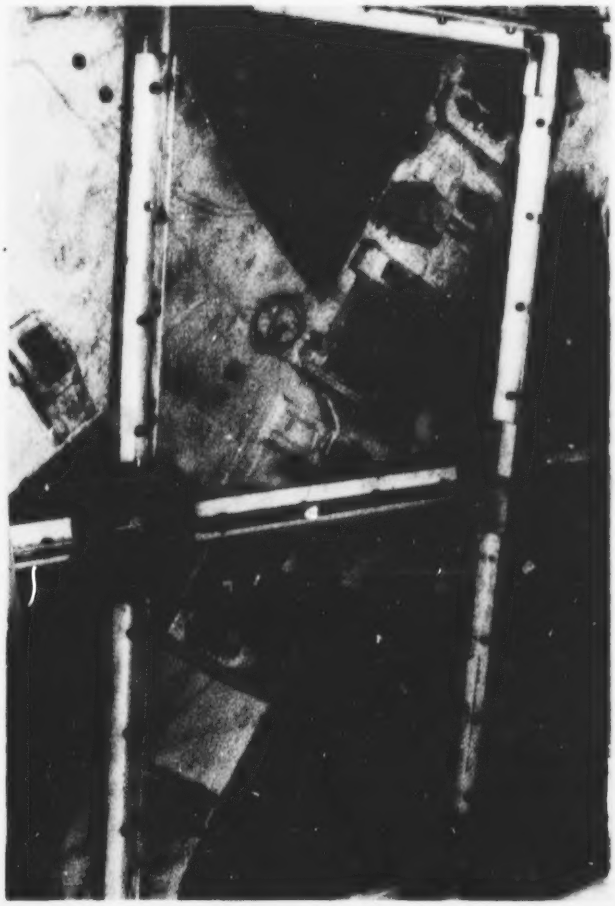
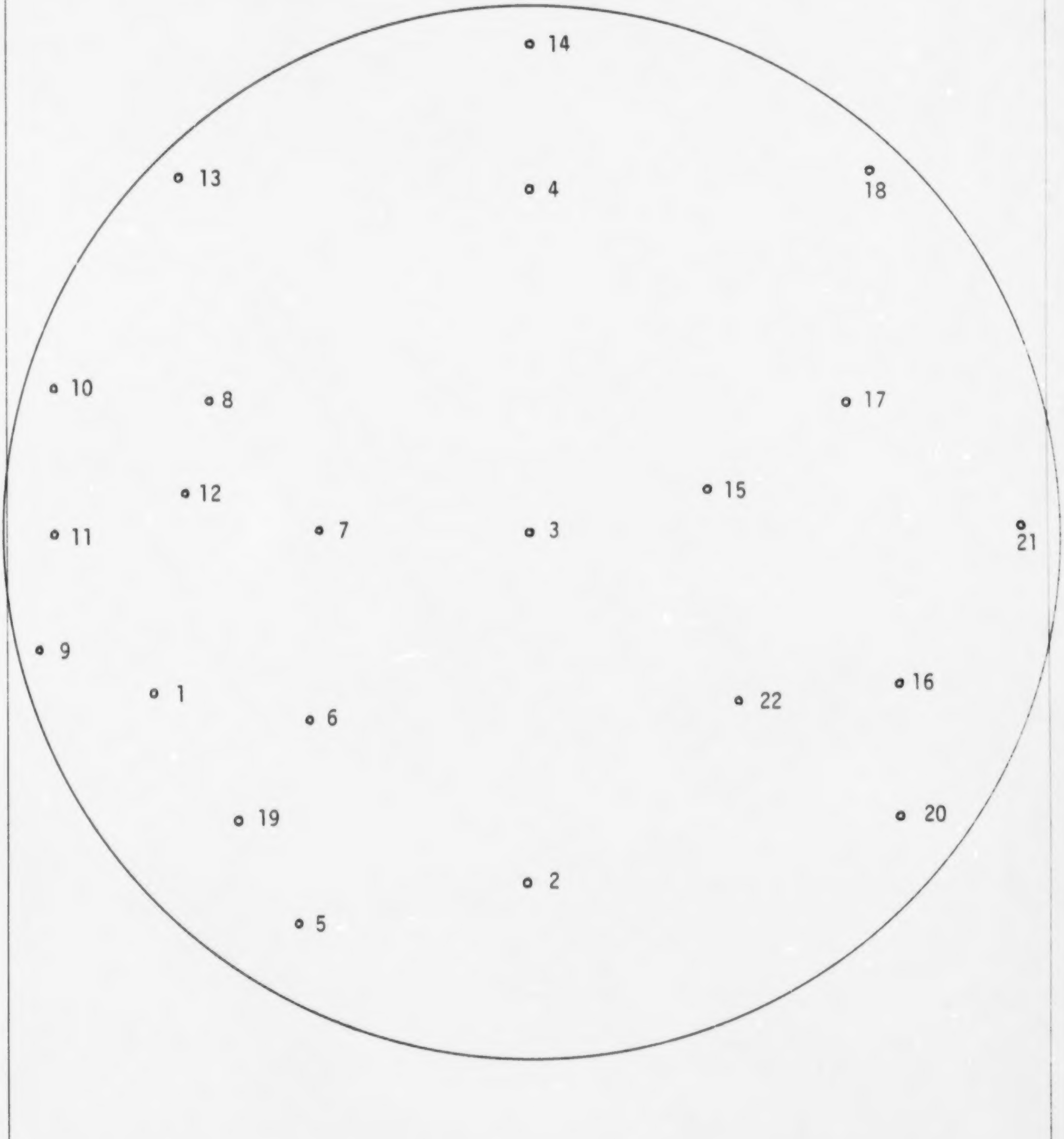


FIGURE 14

Shroud Framework and Marked Blade

FIGURE 15

Tracer Gas Addition Locations


14
13
4
18
10
8
17
12
15
11
7
3
21
9
1
6
22
16
19
20
2
5

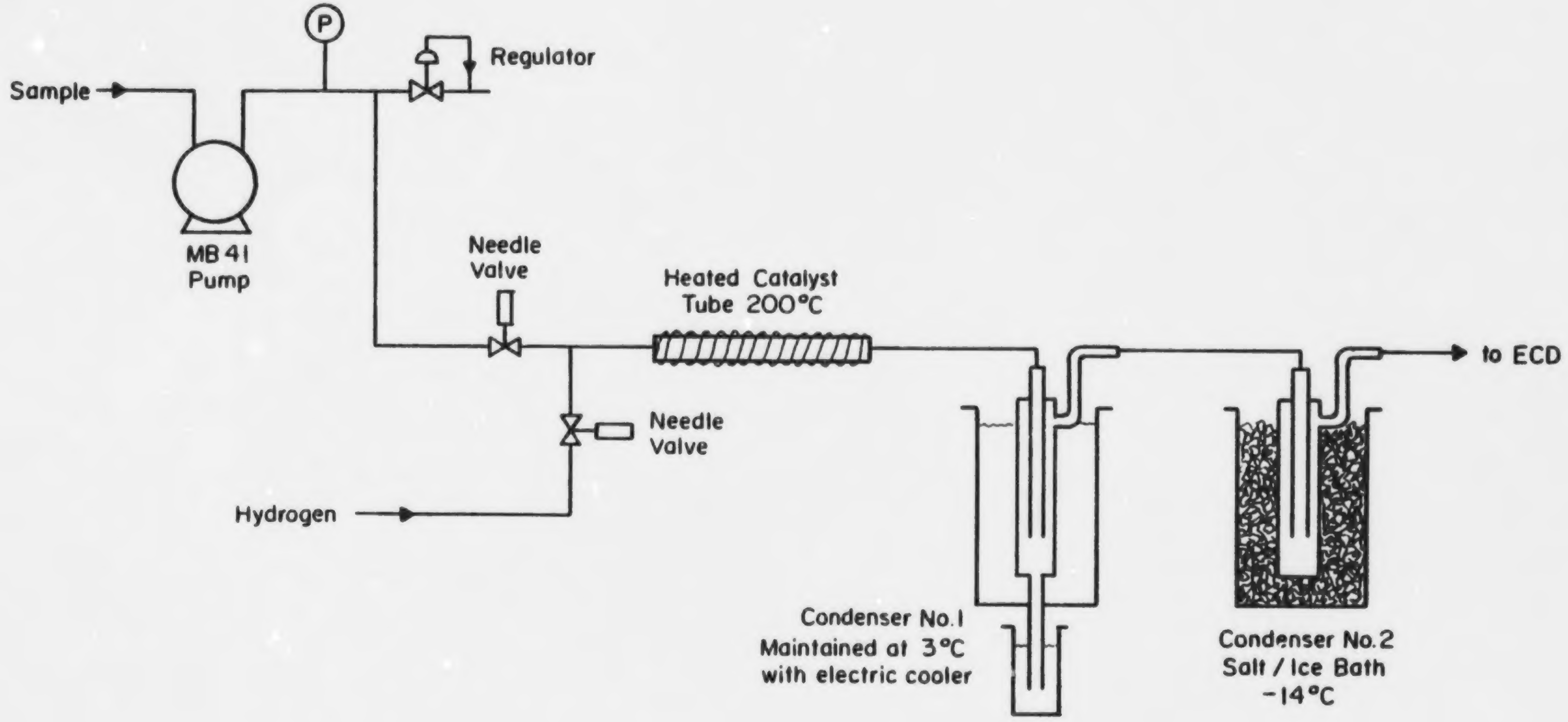

Sample
P
Regulator
MB 41
Pump
Needle
Valve
Heated Catalyst
Tube 200°C
Needle
Valve
Hydrogen
to ECD
Condenser No.1
Maintained at 3°C
with electric cooler
Condenser No.2
Salt / Ice Bath
-14°C

FIGURE 16. CONTINUOUS ECD SYSTEM

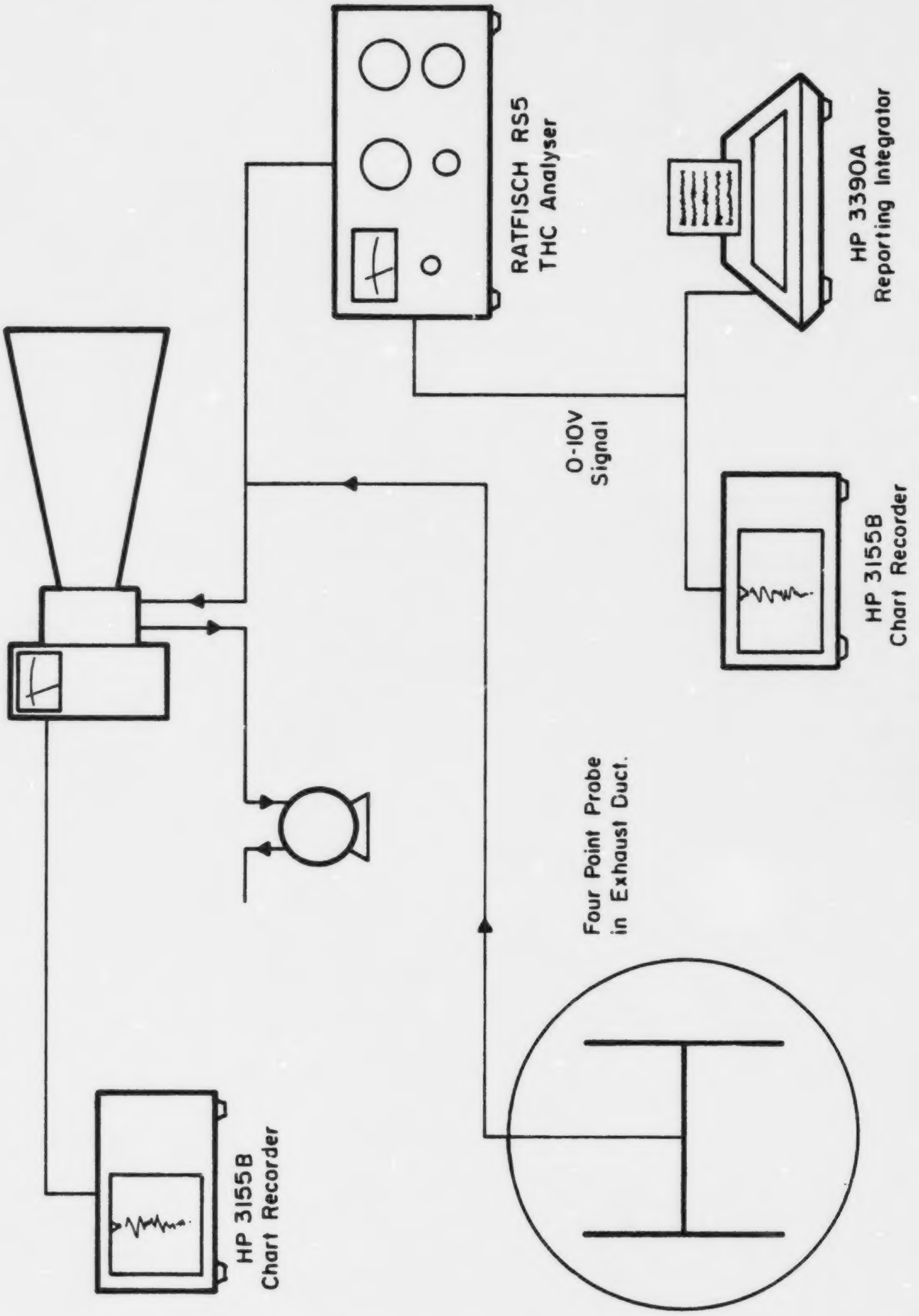

RATFISCH RS5
THC Analyser
HP 3390A
Reporting Integrator
0-10V
Signal
HP 3155B
Chart Recorder
Four Point Probe
in Exhaust Duct.
HP 3155B
Chart Recorder

FIGURE 17. EXHAUST SAMPLING AND ANALYSIS TRAIN.

FIGURE 18 - Sampling Probe and Velocity Measurement Location

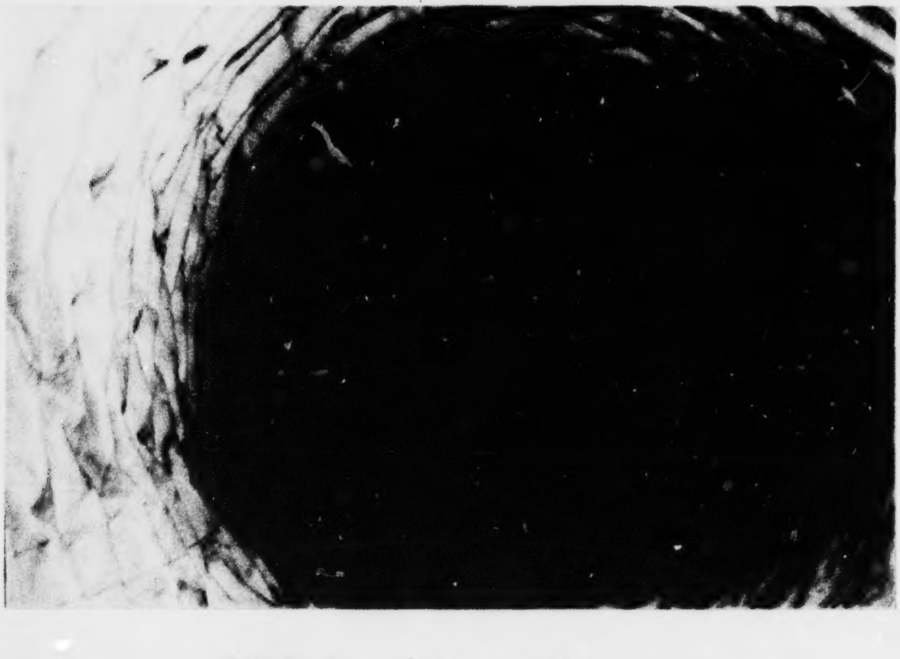


FIGURE 19 - H-type Sampling Probe

FIGURE 20

FIGURE 21

Views of Analytical Set-up

FIGURE 22

Injection Bomb Filling with Propane

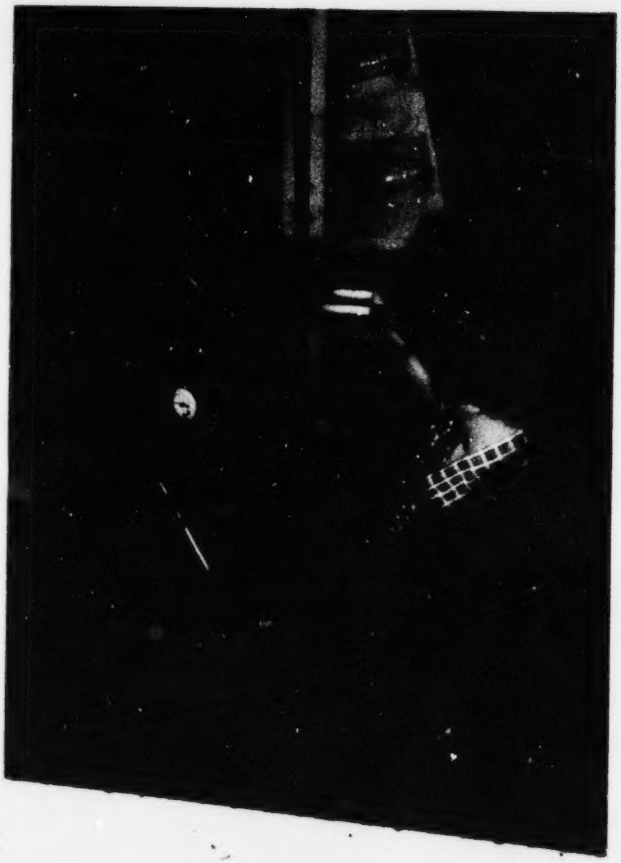
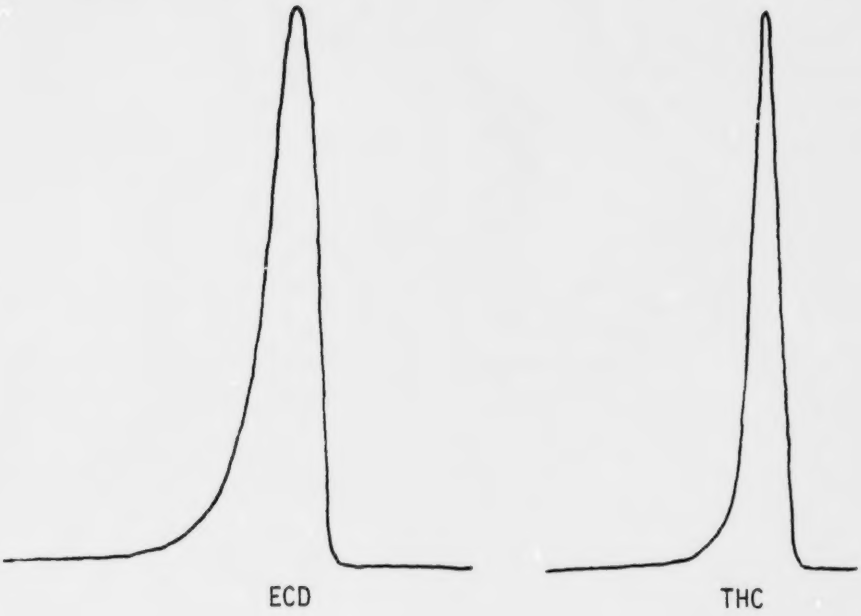


FIGURE 23

FIGURE 24

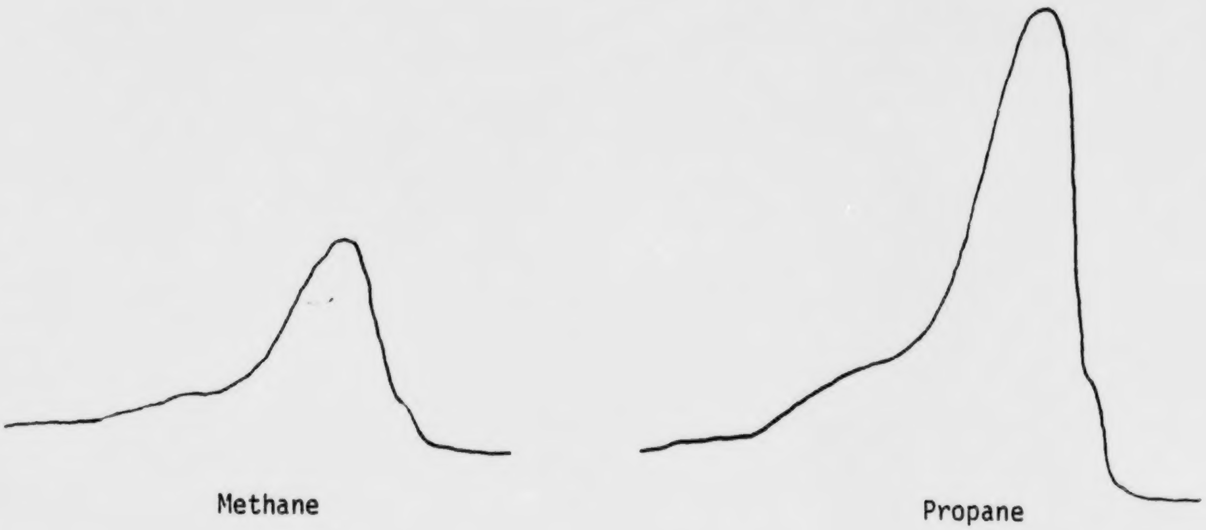
Comparison of GC ECD and THC Recordings



- Responses obtained for same injection of mixed tracer - SF_6 and propane.
- Peak height of THC trace has been scaled to match ECD trace.

FIGURE 25

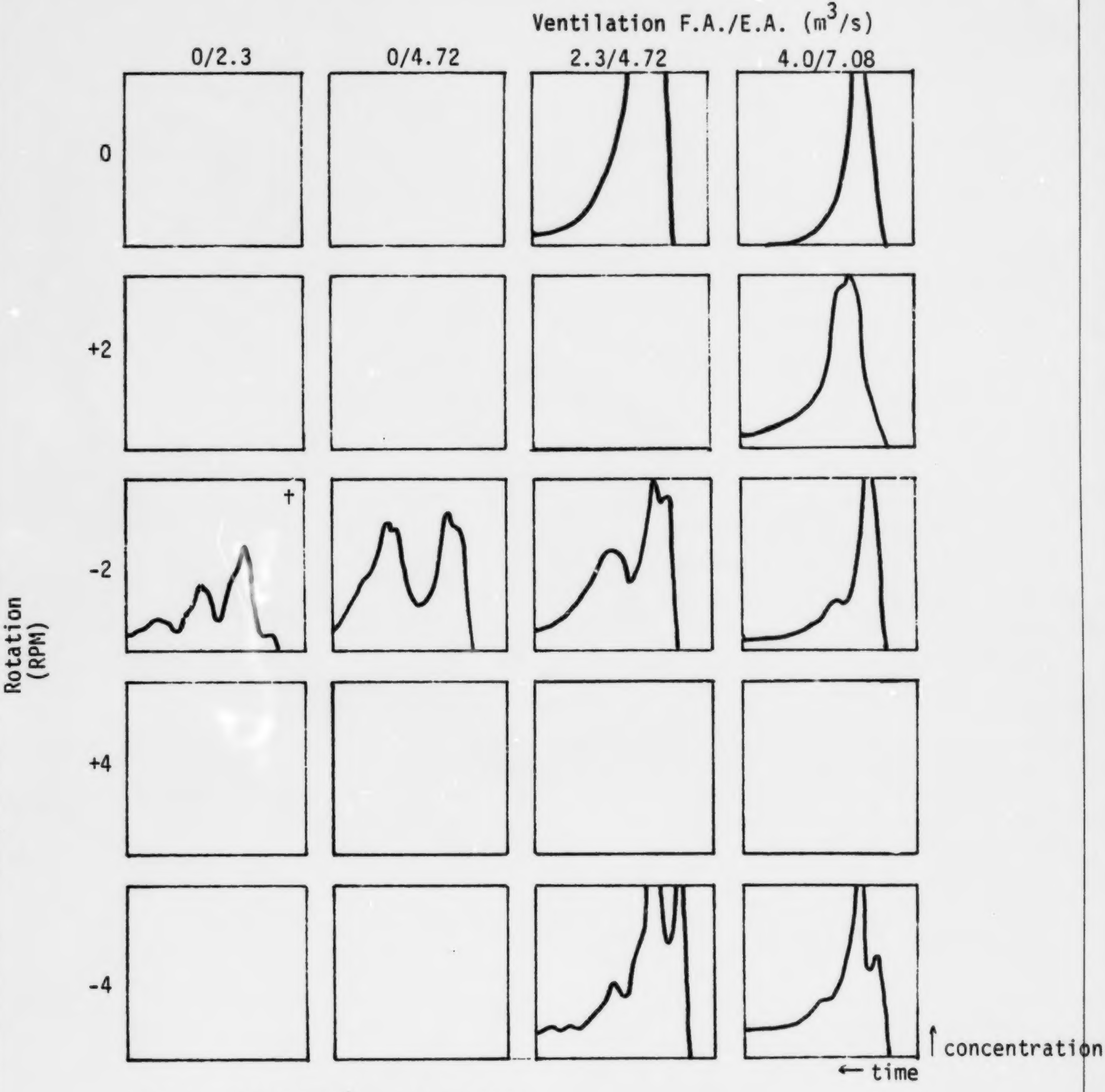
Comparison of Methane and Propane Injections at Same Test Point



- Injected at point #20, 2.3 m^3/s forcing air, 4.72 m^3/s exhaust at 2 RPM cc.

FIGURE 26

Summary of Traces for Injection Point #1



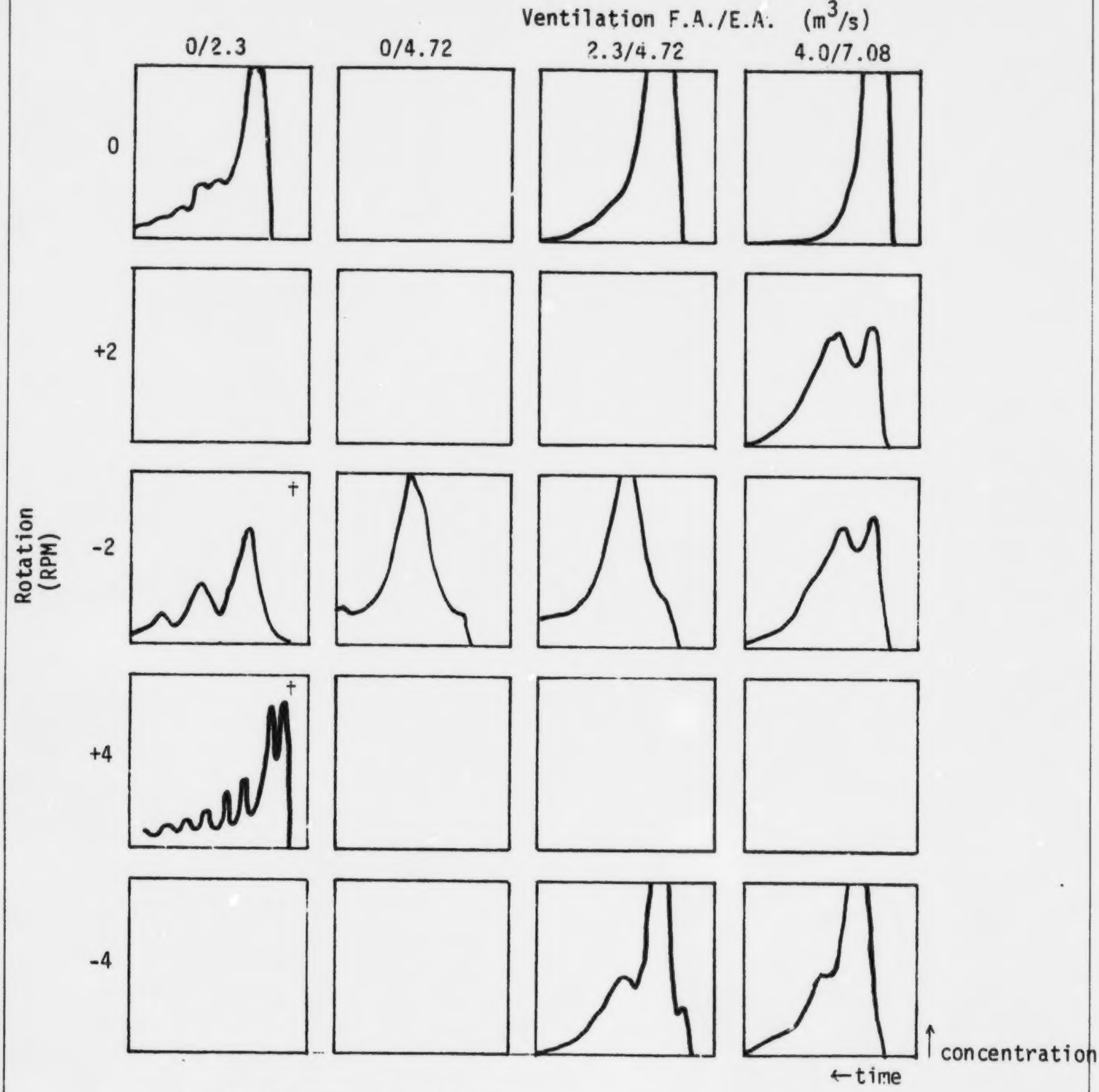
† 0 - 120 seconds, 0 - 12 ppm

All others 0 - 60 seconds, 0 - 6 ppm

F.A. = forcing air
E.A. = exhaust air

FIGURE 27

Summary of Traces for Injection Point #2

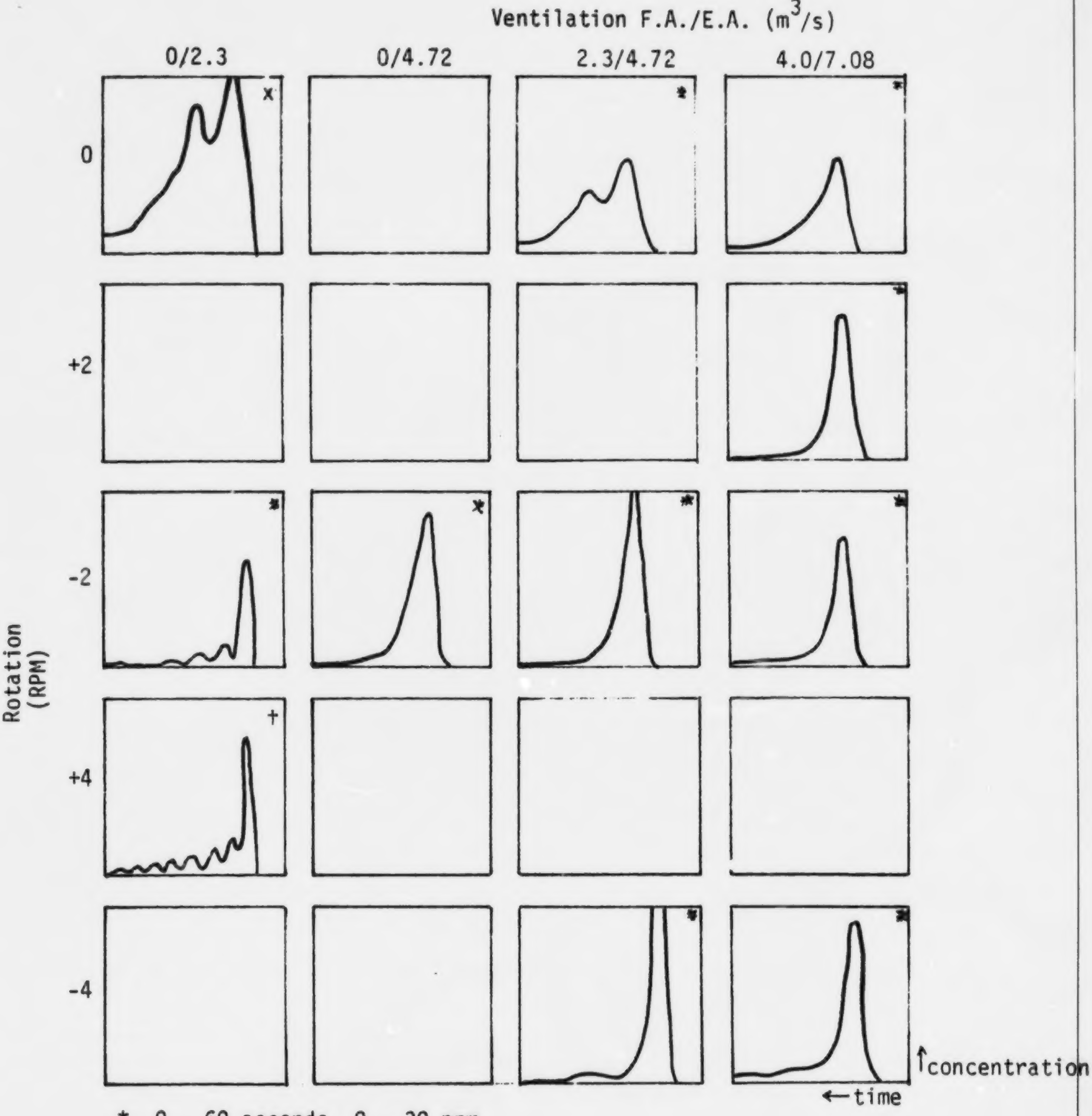


† 0 - 120 seconds, 0 - 12 ppm

All others 0 - 60 seconds, 0 - 6 ppm

FIGURE 28

Summary of Traces for Injection Point #3



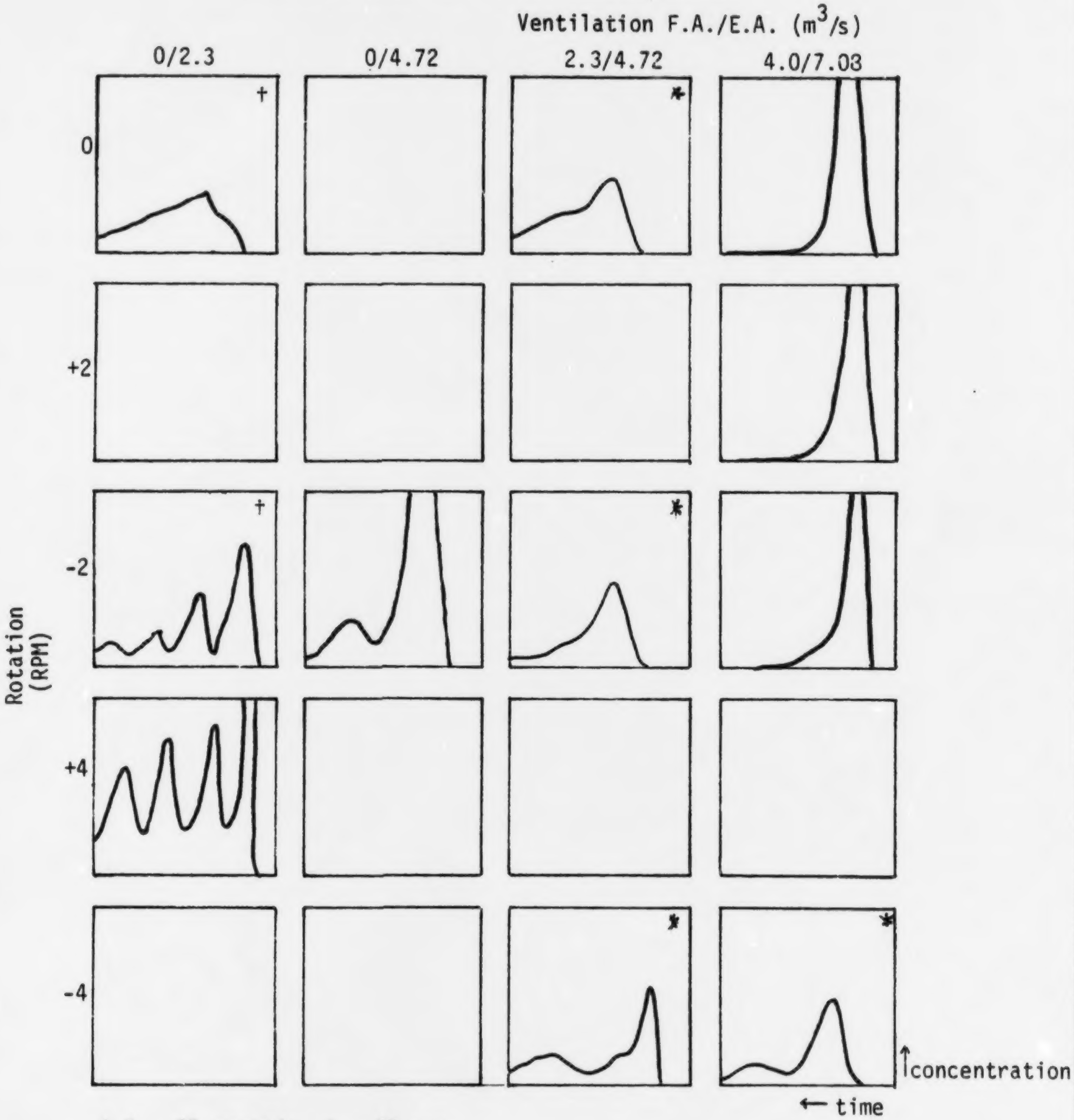
* 0 - 60 seconds, 0 - 30 ppm

x 0 - 60 seconds, 0 - 12 ppm

† 0 - 120 seconds, 0 - 12 ppm

FIGURE 29

Summary of Traces for Injection Point #4

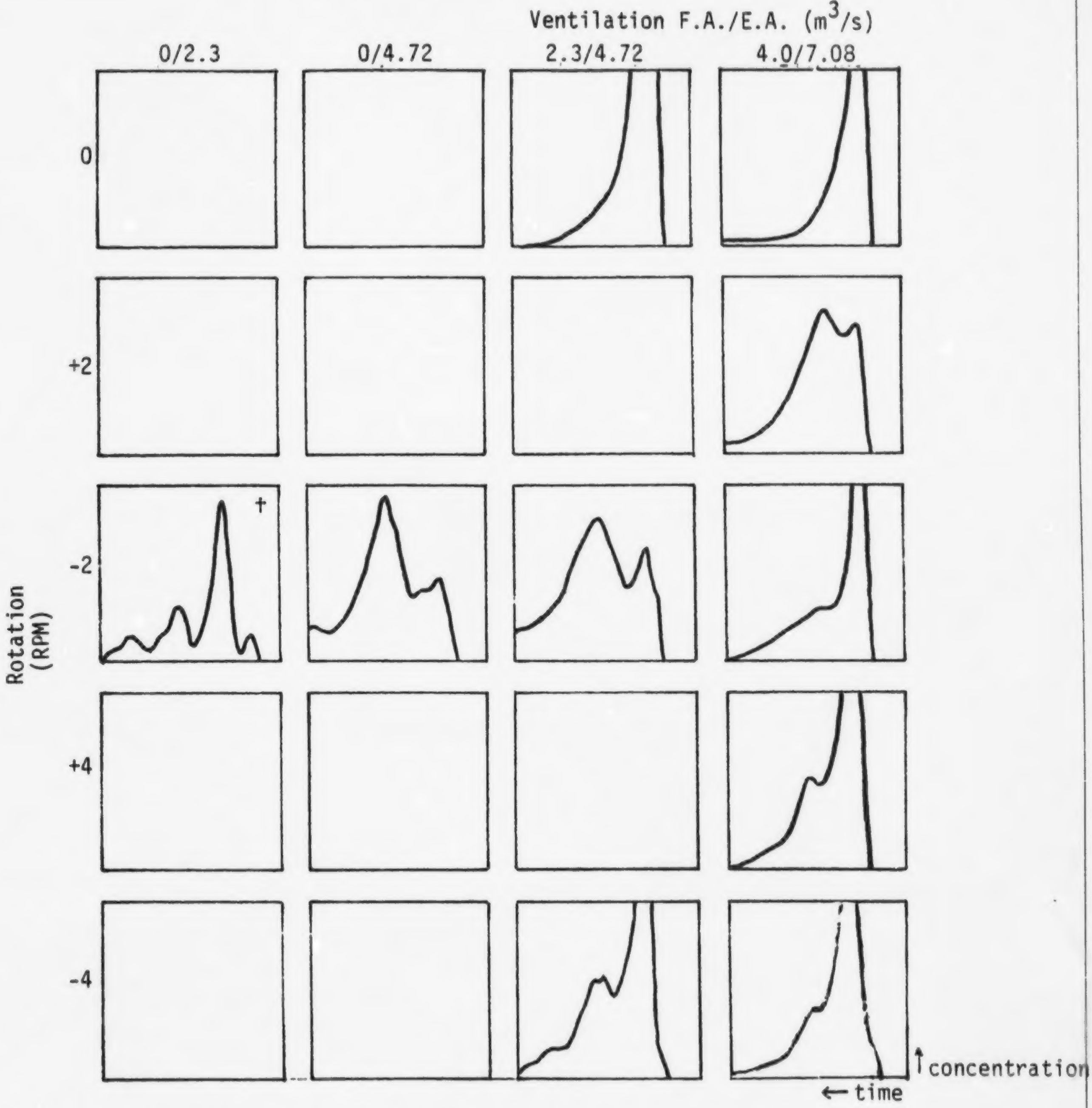


* 0 - 60 seconds, 0 - 30 ppm

† 0 - 120 seconds, 0 - 12 ppm

FIGURE 30

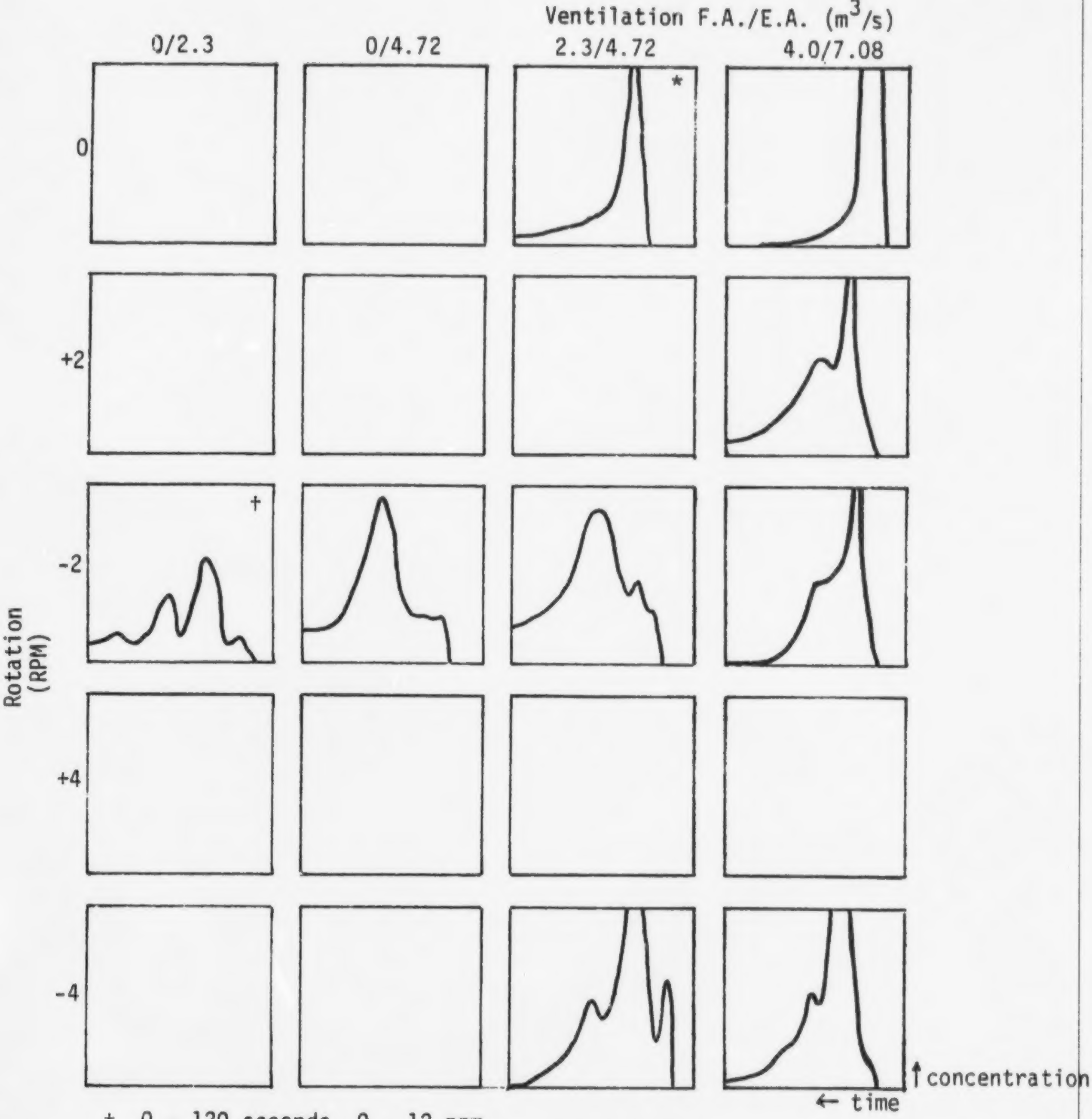
Summary of Traces for Injection Point #5



† 0 - 120 seconds, 0 - 12 ppm

FIGURE 31

Summary of Traces for Injection Point #6

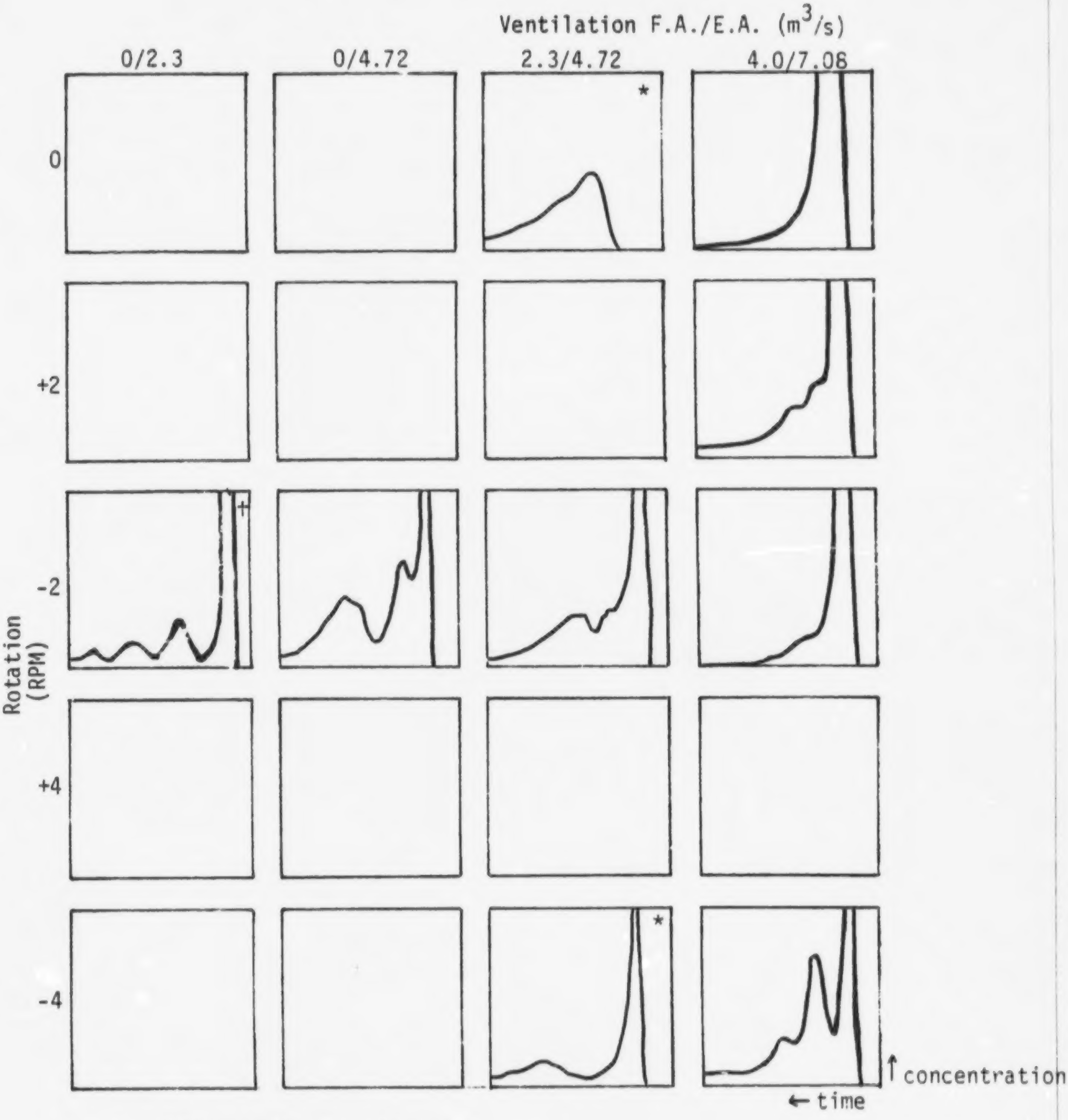


† 0 - 120 seconds, 0 - 12 ppm

* 0 - 60 seconds, 0 - 30 ppm

FIGURE 32

Summary of Traces for Injection Point #7

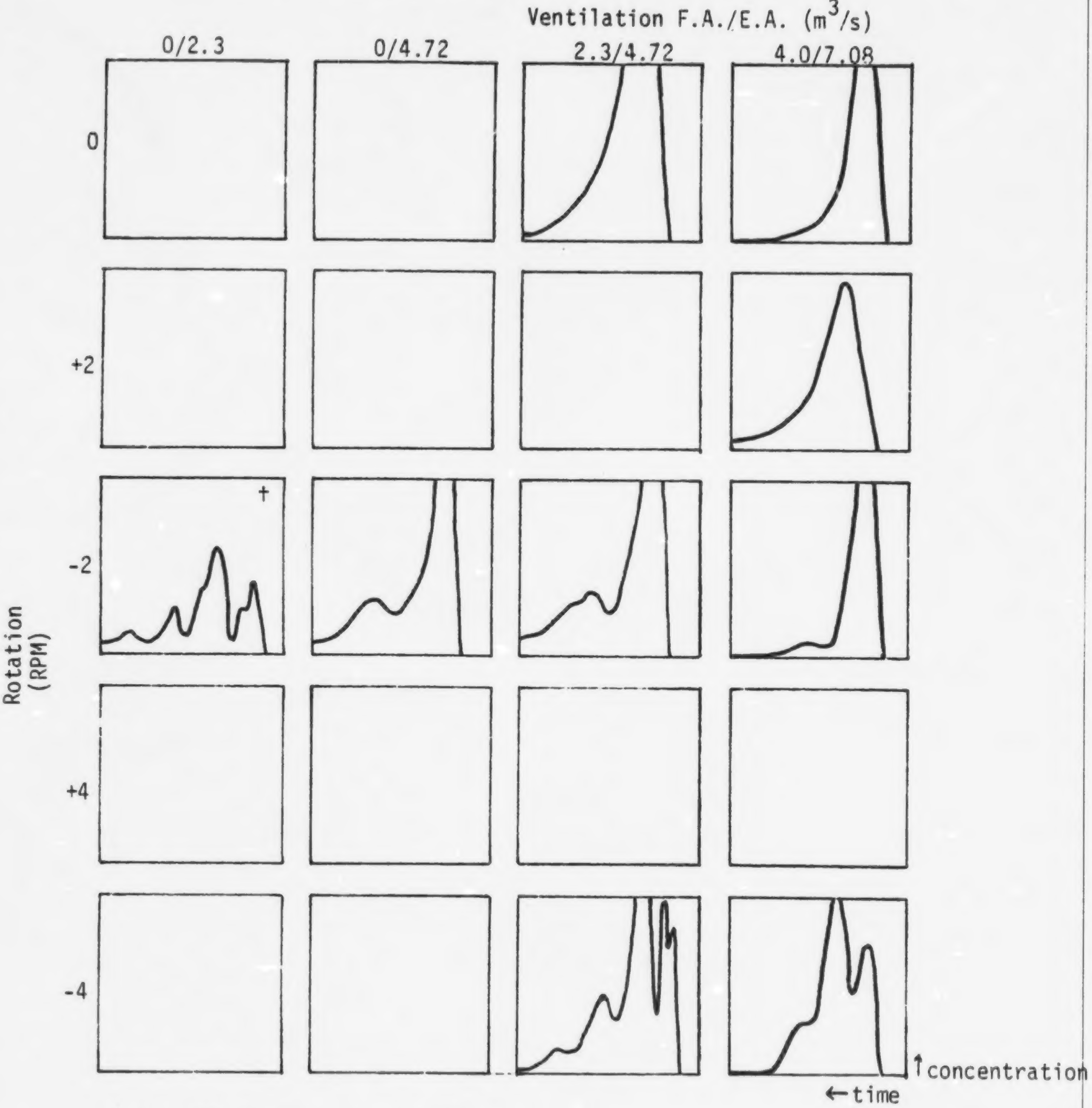


† 0 - 120 seconds, 0 - 12 ppm

* 0 - 60 seconds, 0 - 30 ppm

FIGURE 33

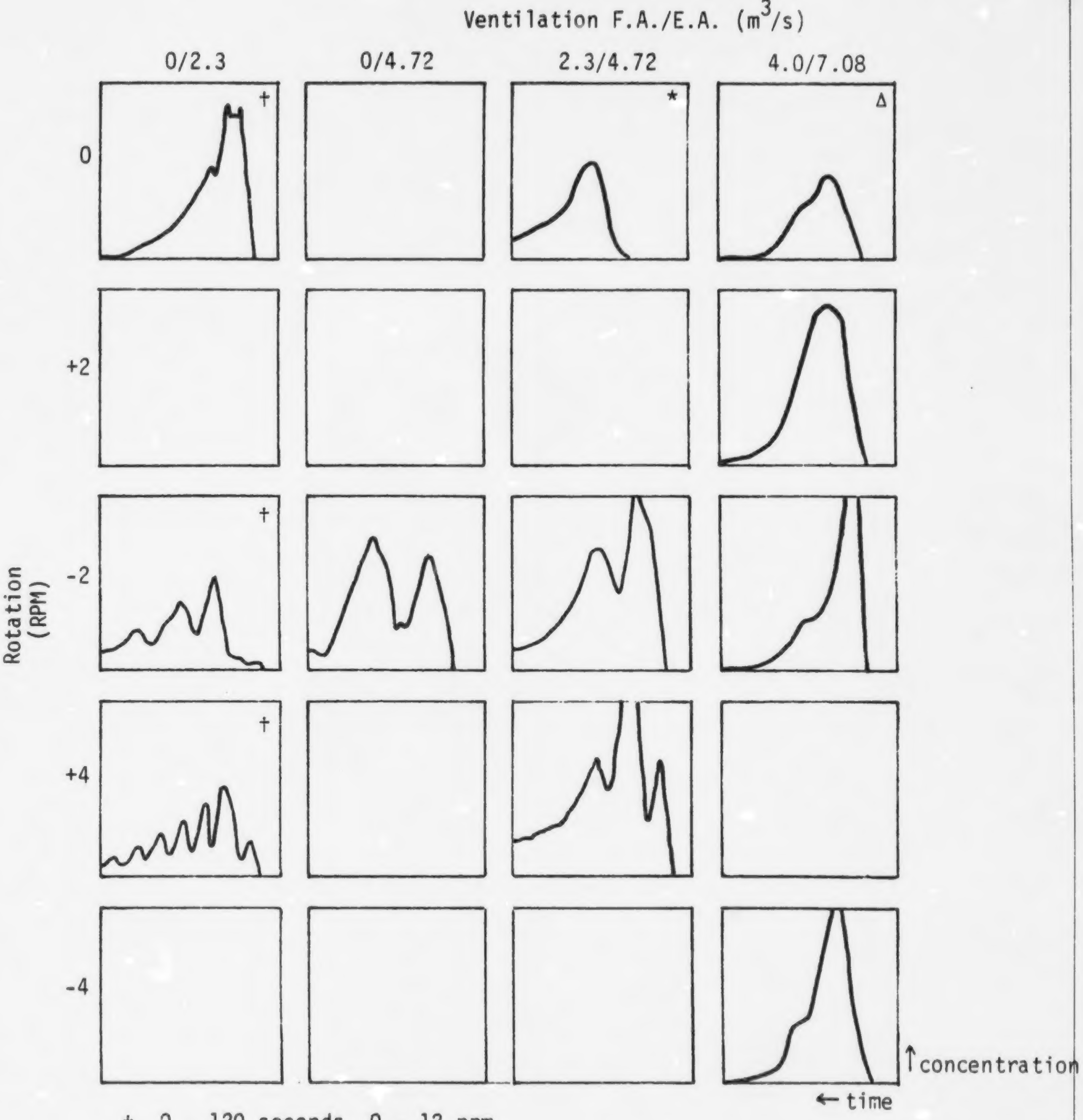
Summary of Traces for Injection Point #8



† 0 - 120 seconds, 0 - 12 ppm

FIGURE 34

Summary of Traces for Injection Point #9



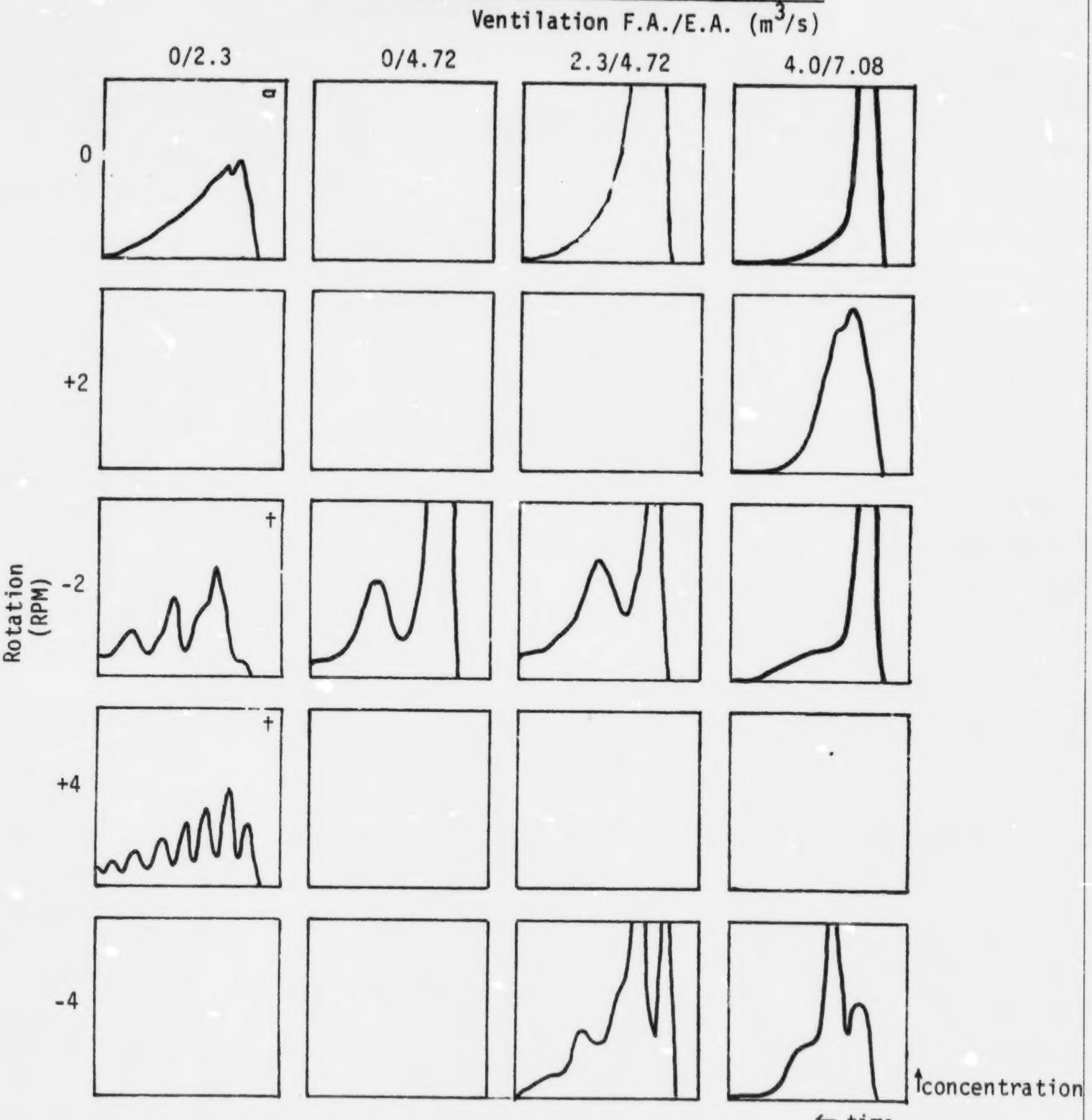
† 0 - 120 seconds, 0 - 12 ppm

* 0 - 60 seconds, 0 - 30 ppm

Δ Before stratification

FIGURE 35

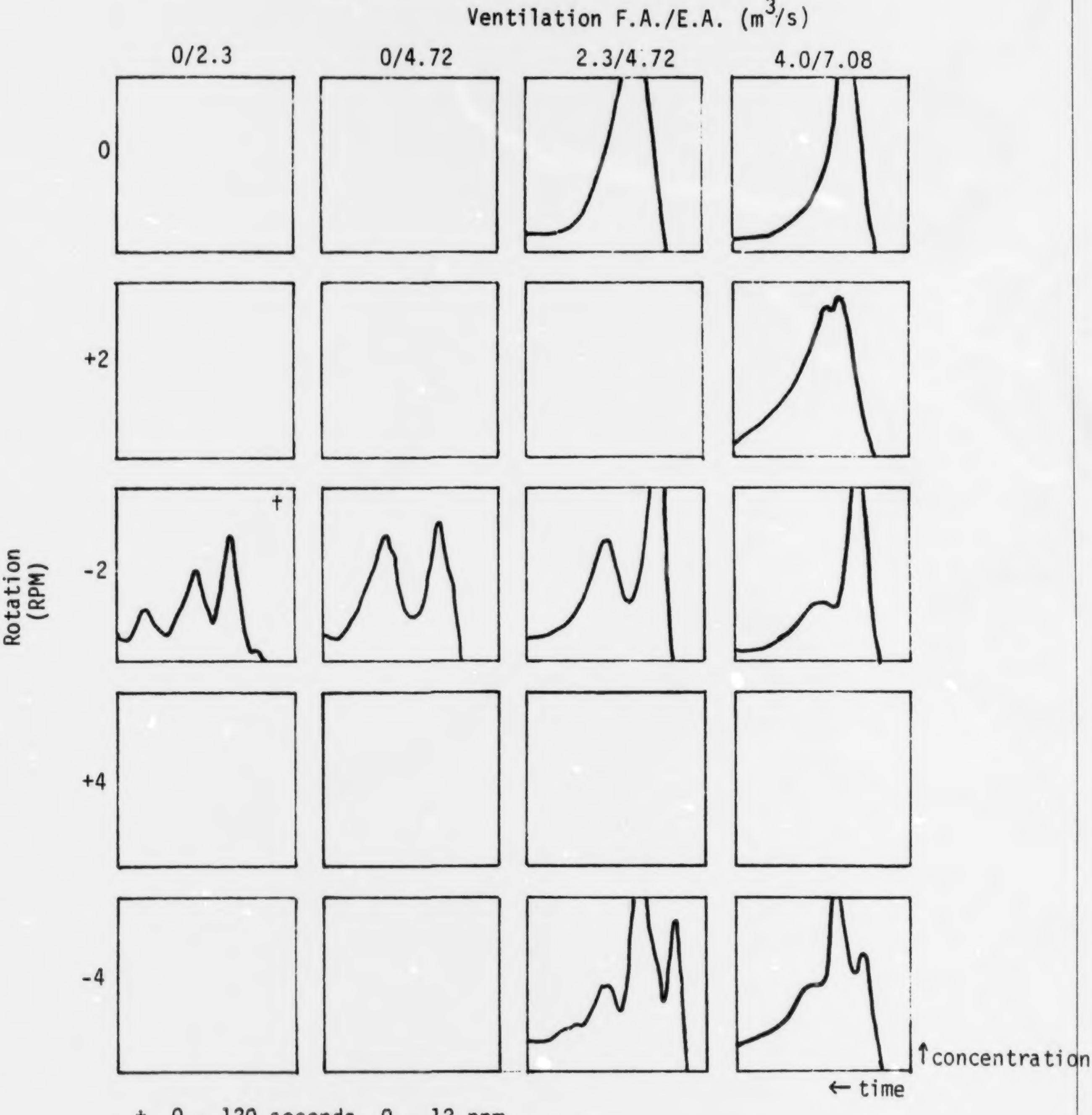
Summary of Traces for Injection Point #10



† 0 - 120 seconds, 0 - 12 ppm

FIGURE 36

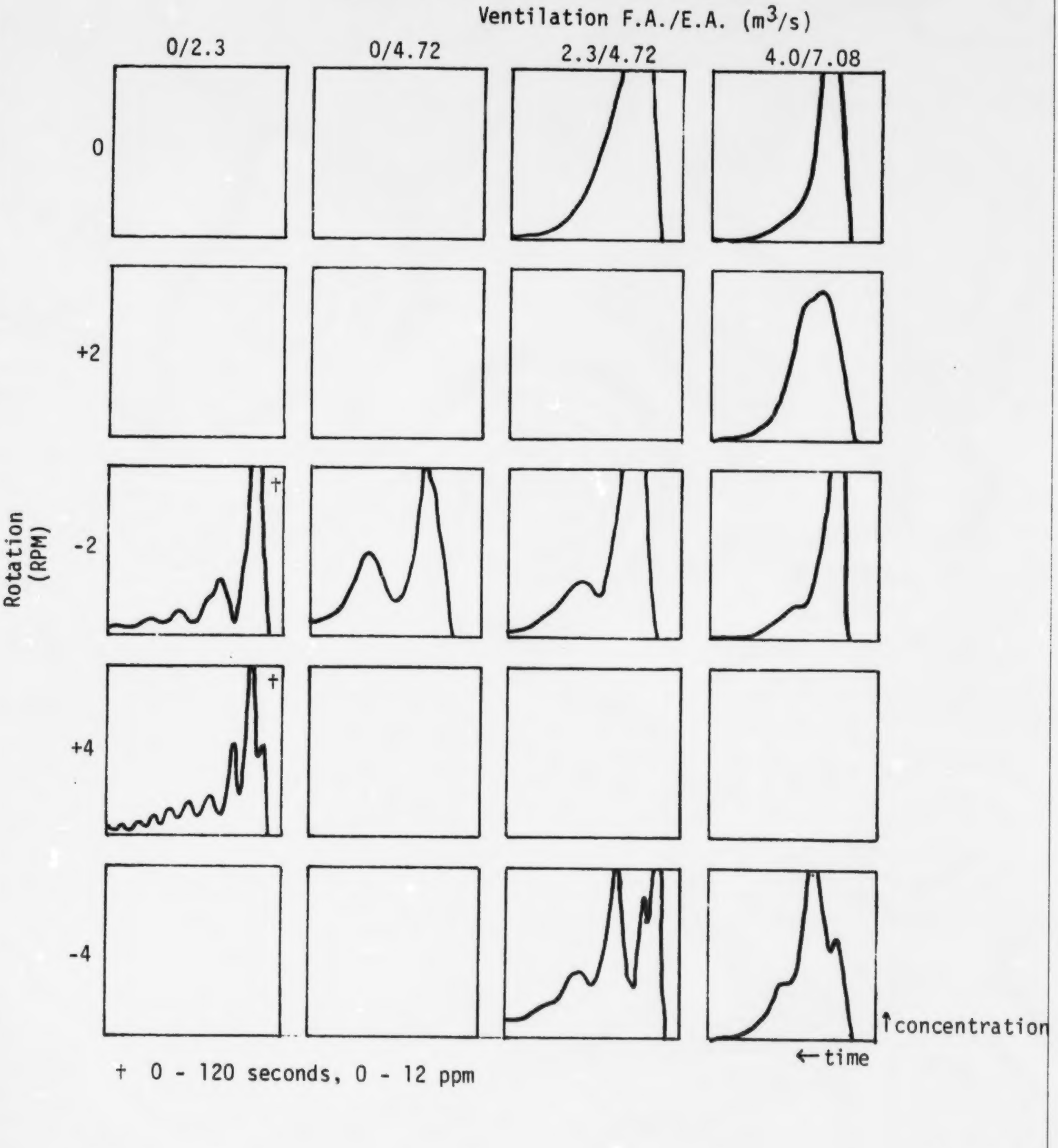
Summary of Traces for Injection Point #11



† 0 - 120 seconds, 0 - 12 ppm

FIGURE 37

Summary of Traces for Injection Point #12

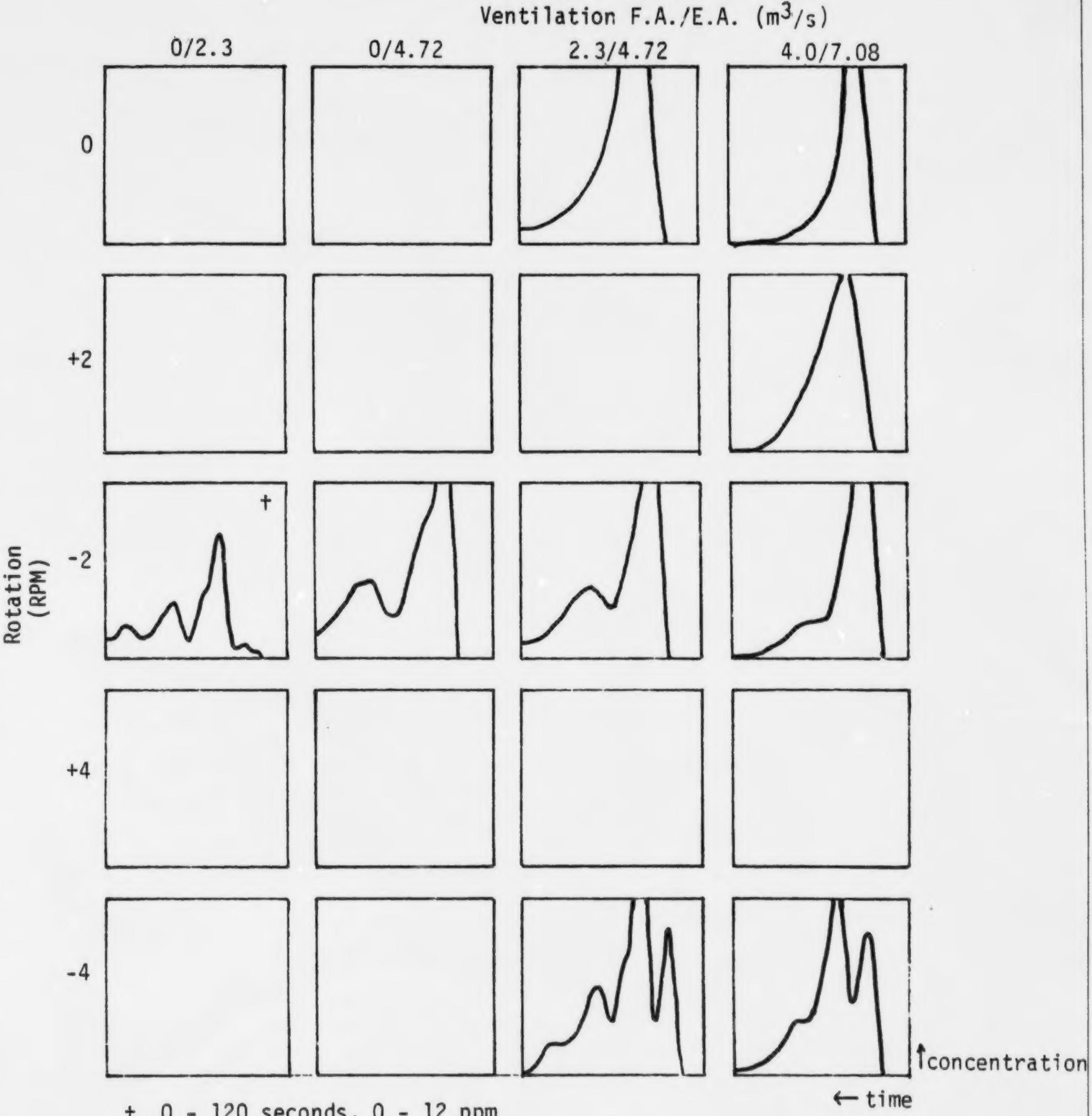


† 0 - 120 seconds, 0 - 12 ppm

ORF

FIGURE 38

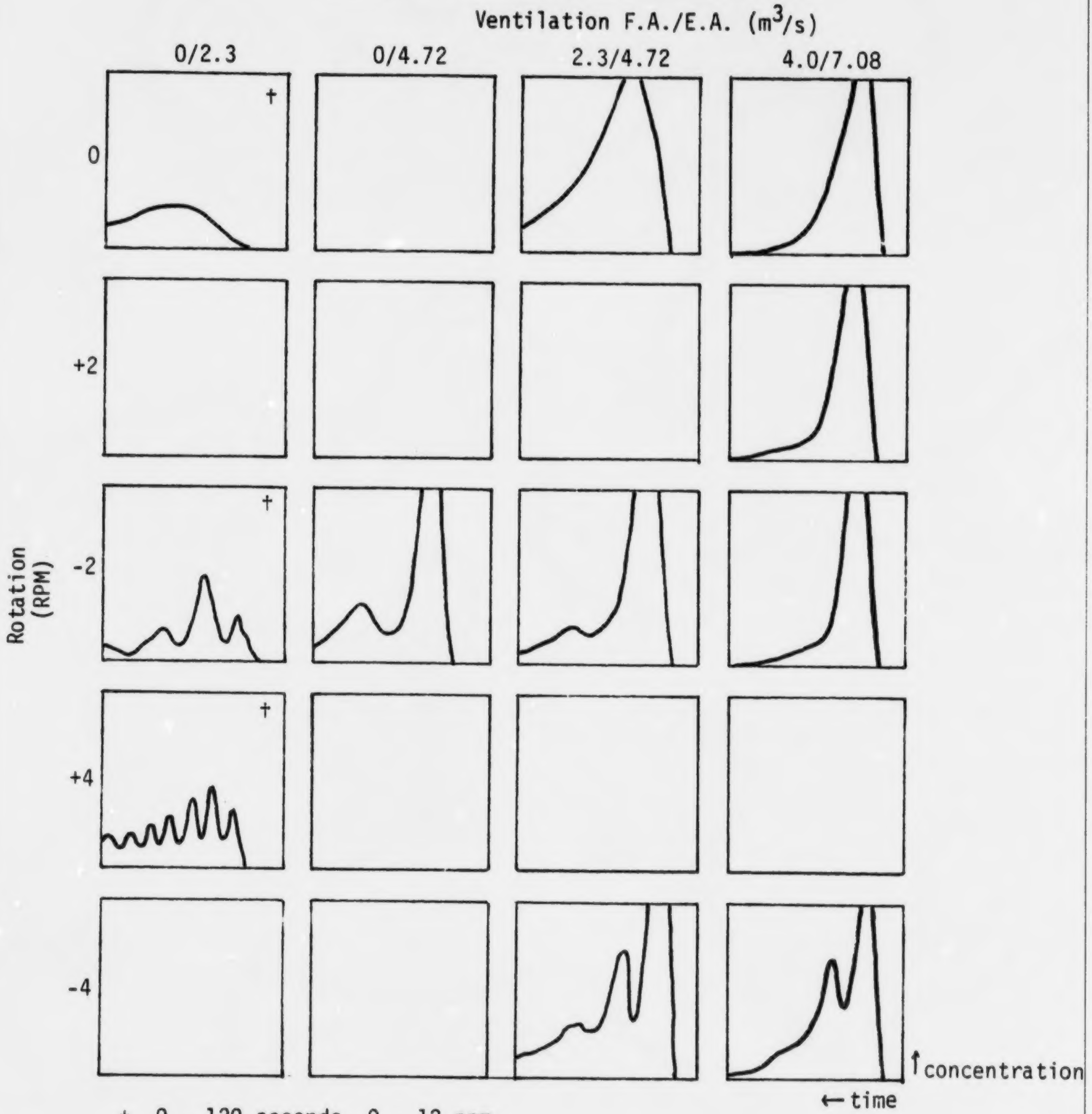
Summary of Traces for Injection Point #13



† 0 - 120 seconds, 0 - 12 ppm

FIGURE 39

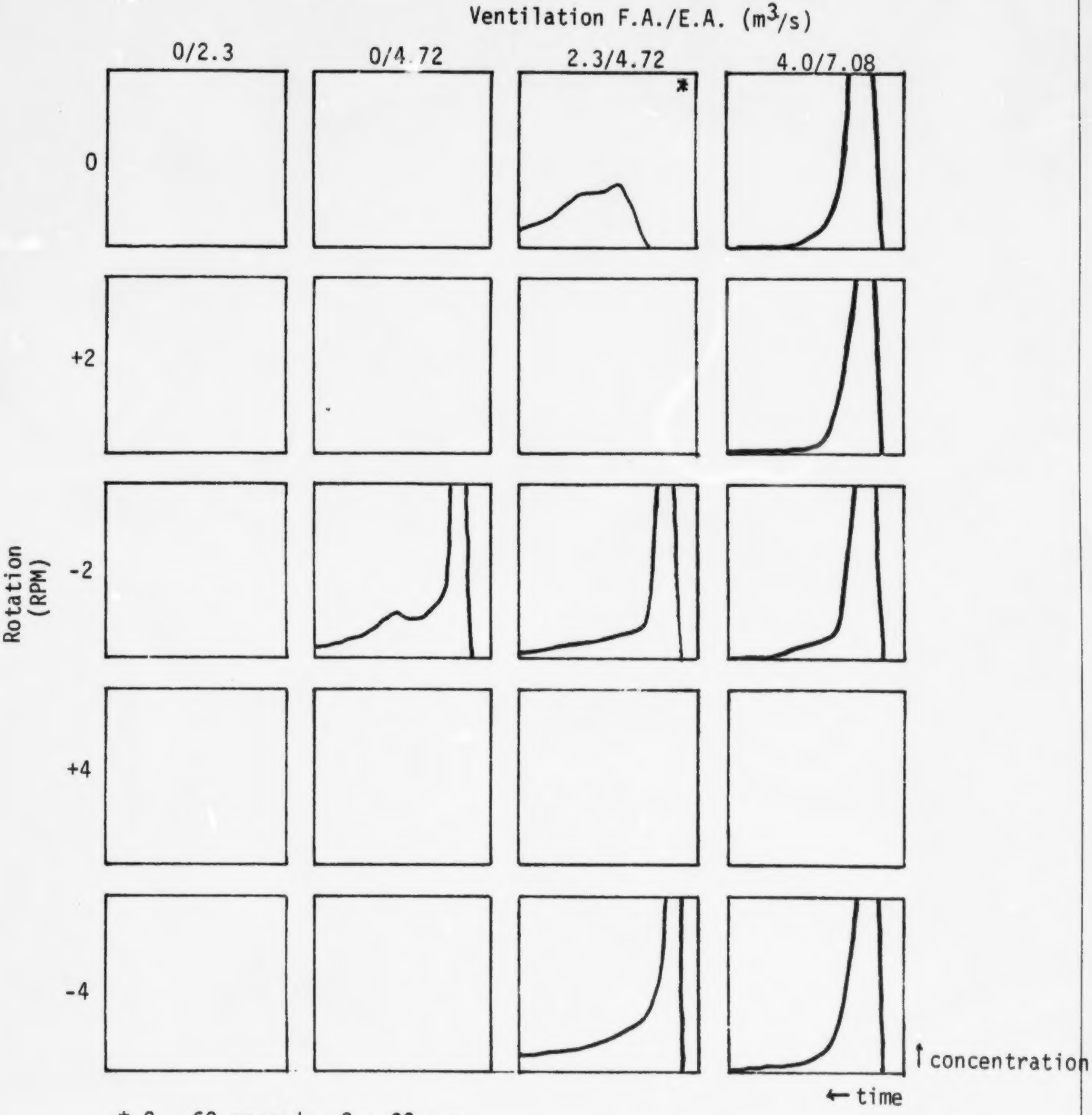
Summary of Traces for Injection Point #14



† 0 - 120 seconds, 0 - 12 ppm

FIGURE 40

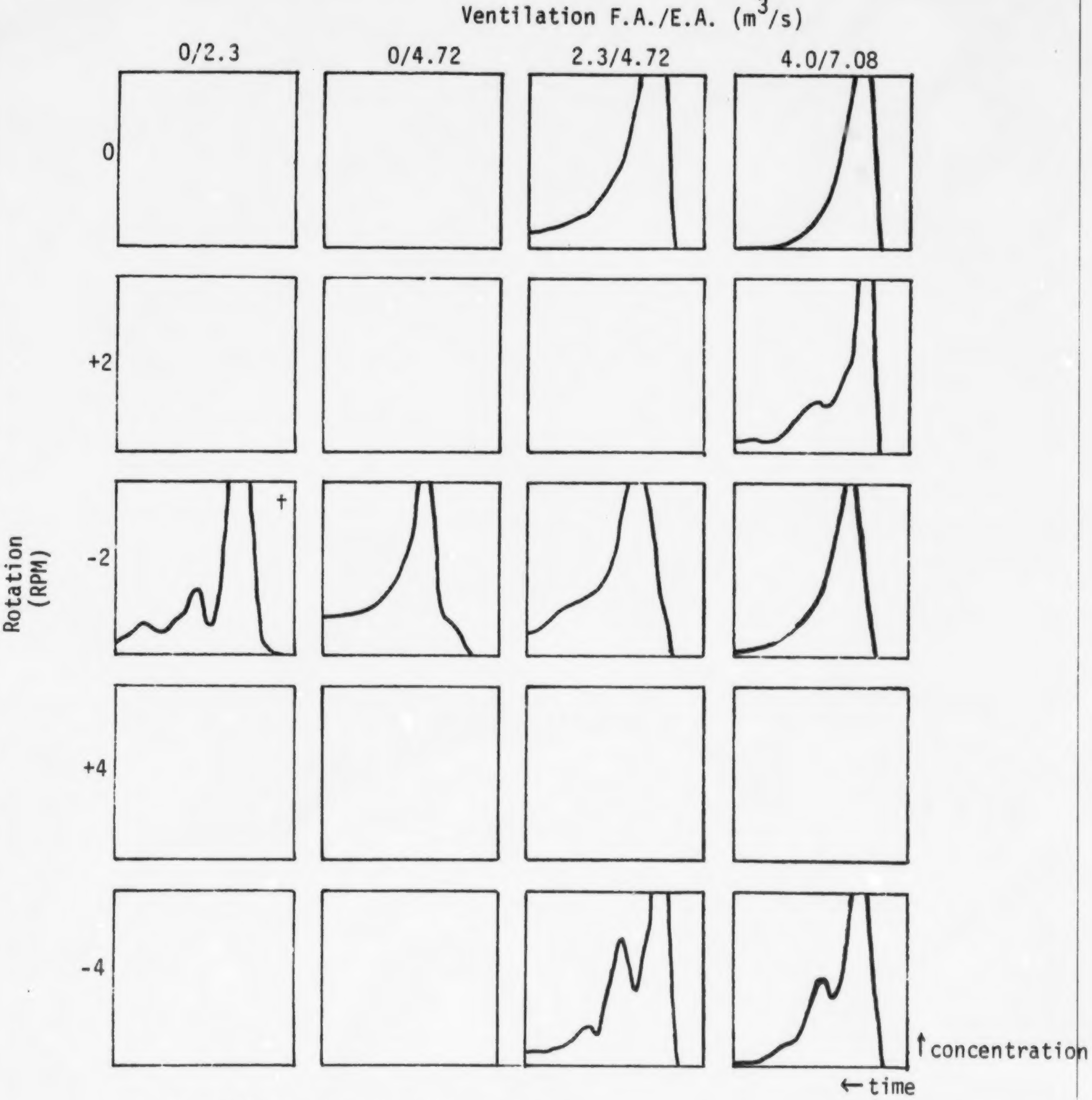
Summary of Traces for Injection Point #15



* 0 - 60 seconds, 0 - 30 ppm

FIGURE 41

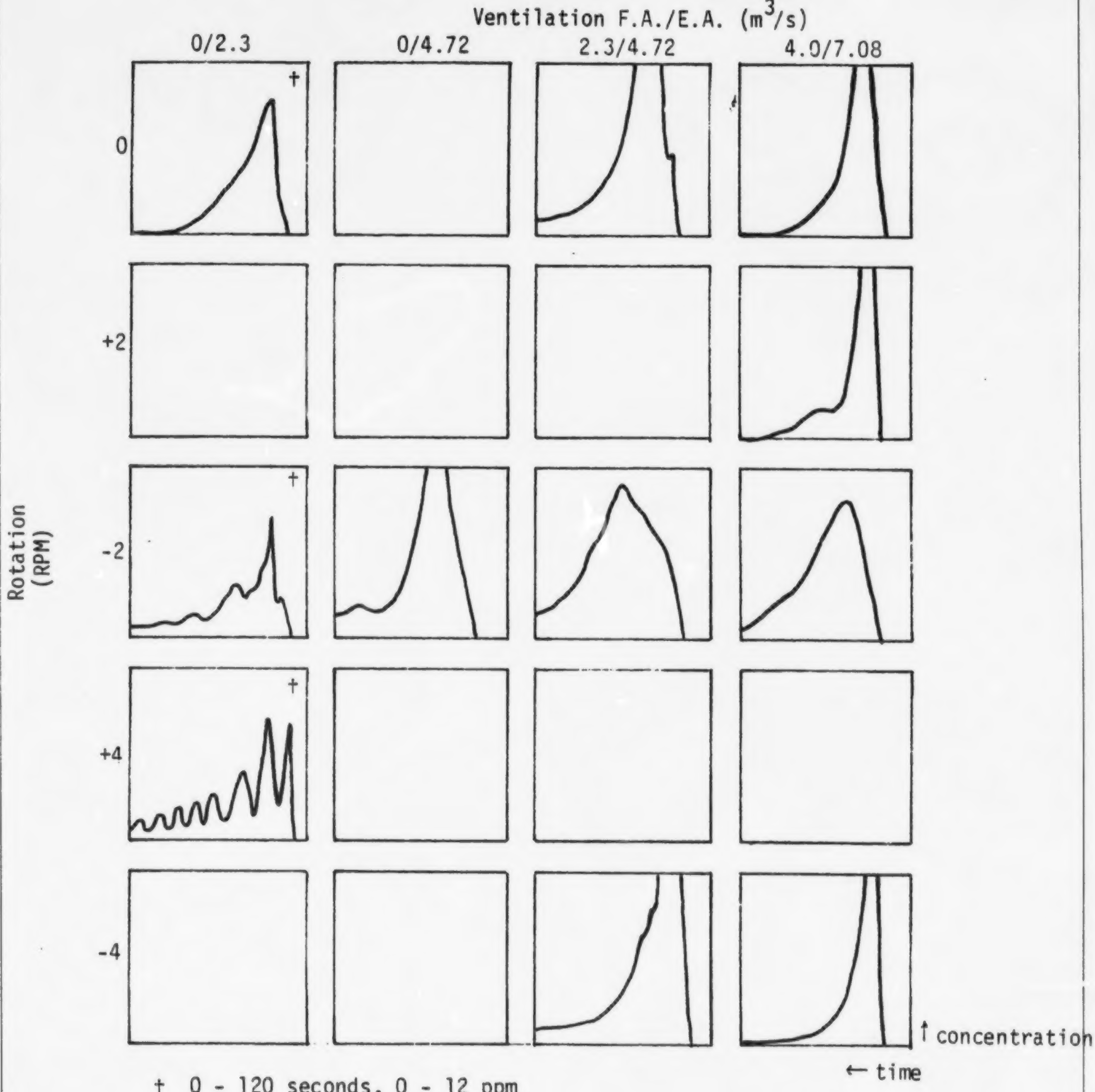
Summary of Traces for Injection Point #16



† 0 - 120 seconds, 0 - 12 ppm

FIGURE 42

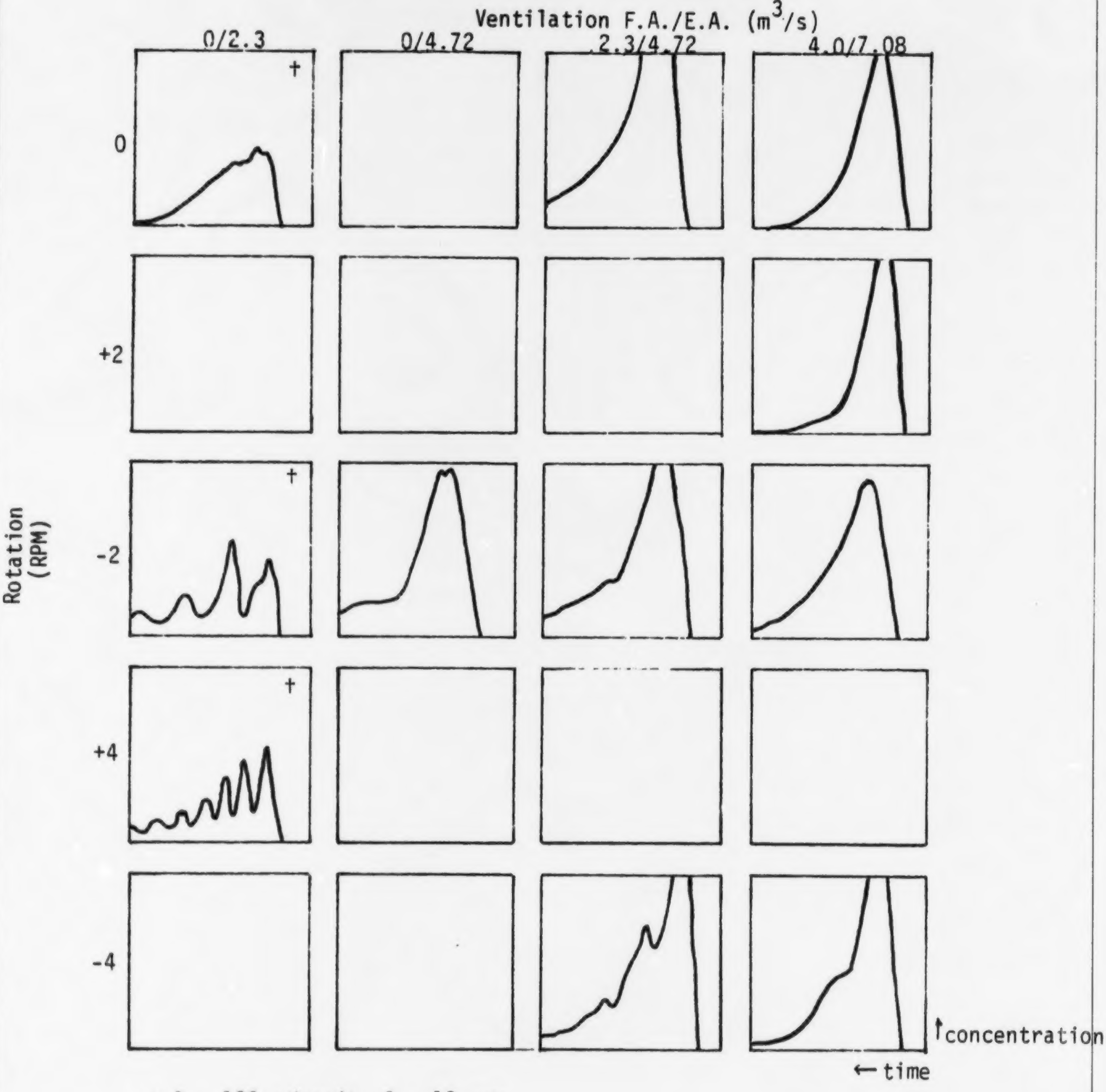
Summary of Traces for Injection Point #17



† 0 - 120 seconds, 0 - 12 ppm

FIGURE 43

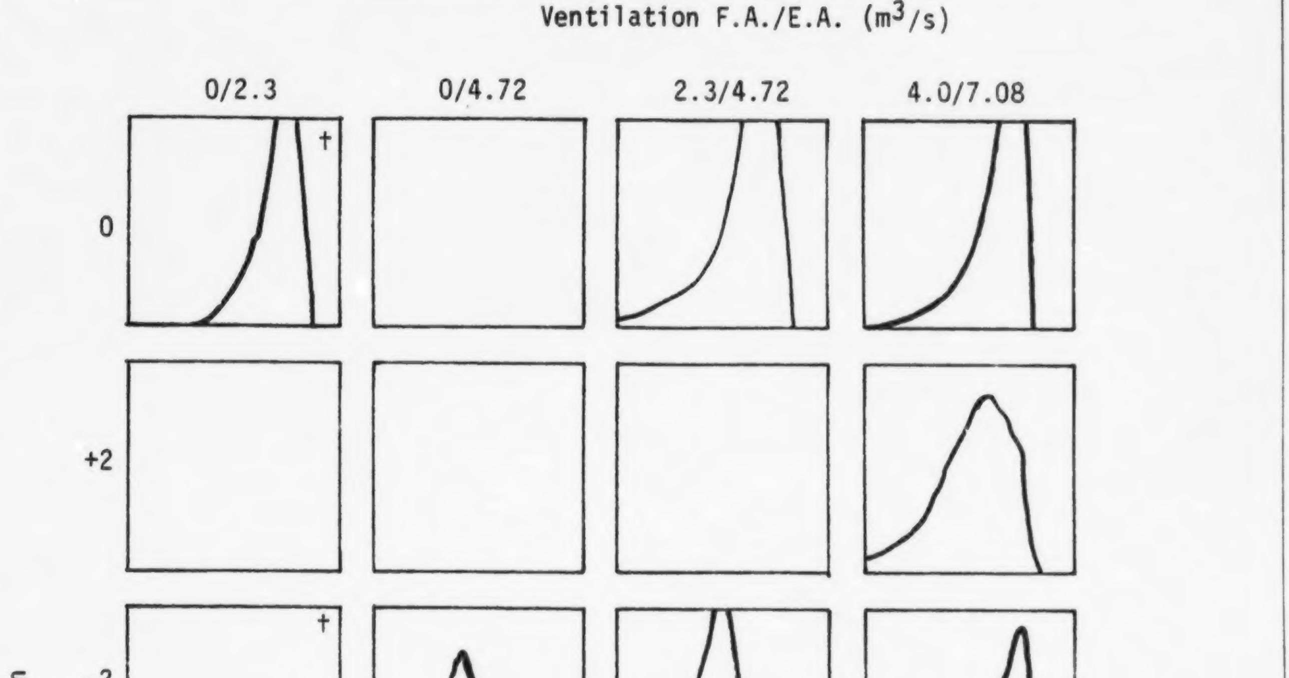
Summary of Traces for Injection Point #18



† 0 - 120 seconds, 0 - 12 ppm

FIGURE 44

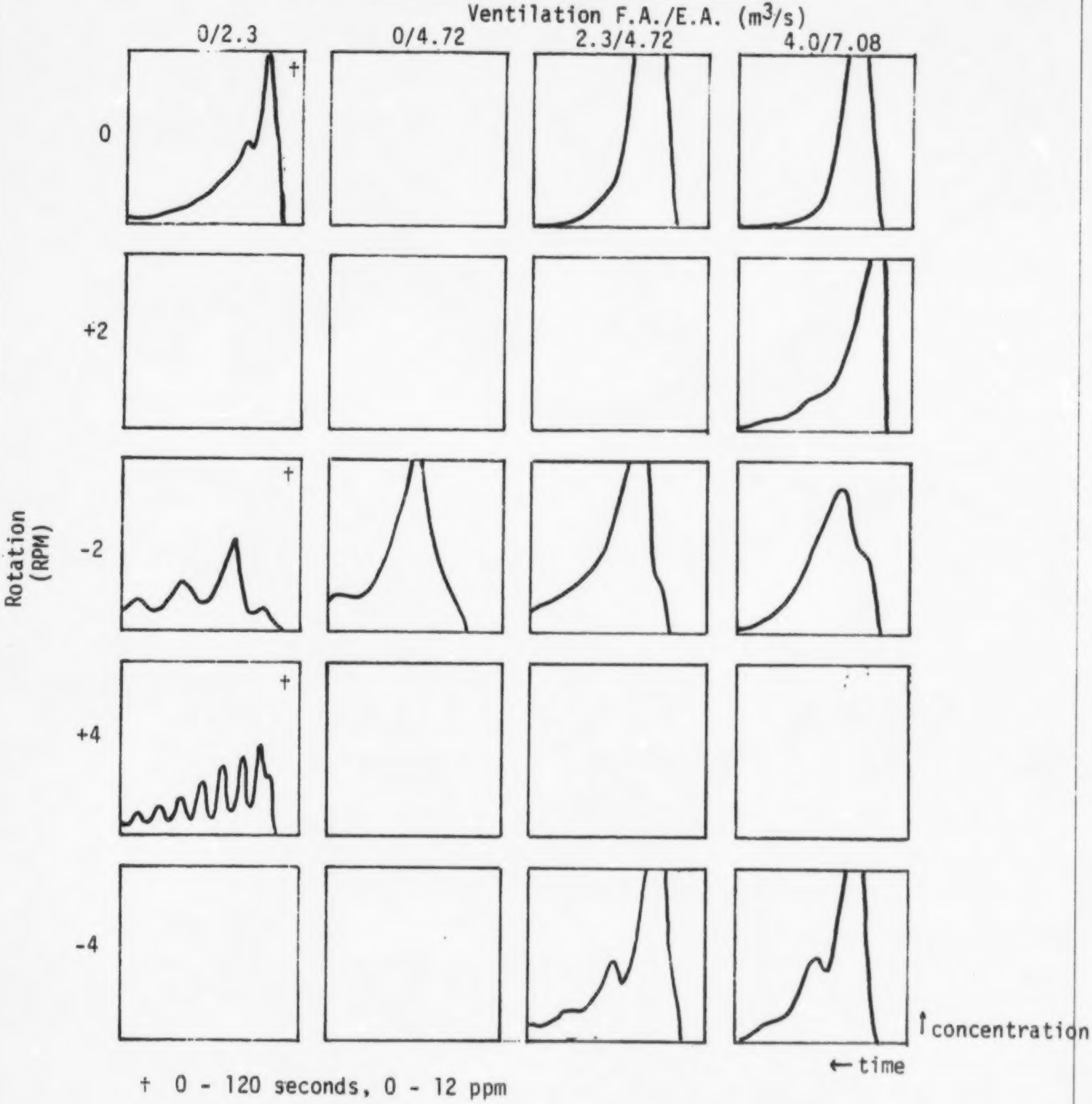
Summary of Traces for Injection Point #19



† 0 - 120 seconds, 0 - 12 ppm

FIGURE 45

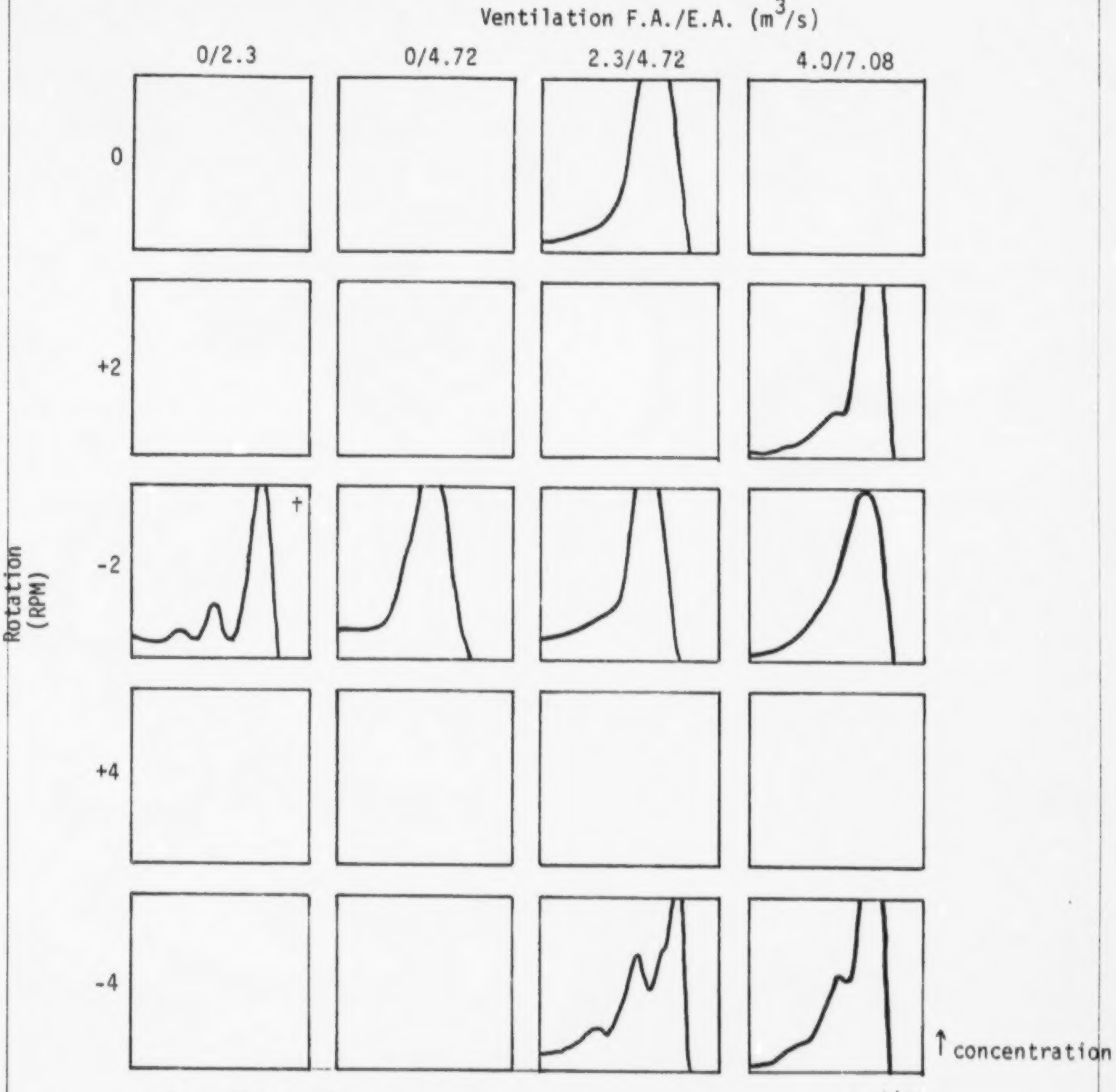
Summary of Traces for Injection Point #20



† 0 - 120 seconds, 0 - 12 ppm

FIGURE 46

Summary of Traces for Injection Point #21

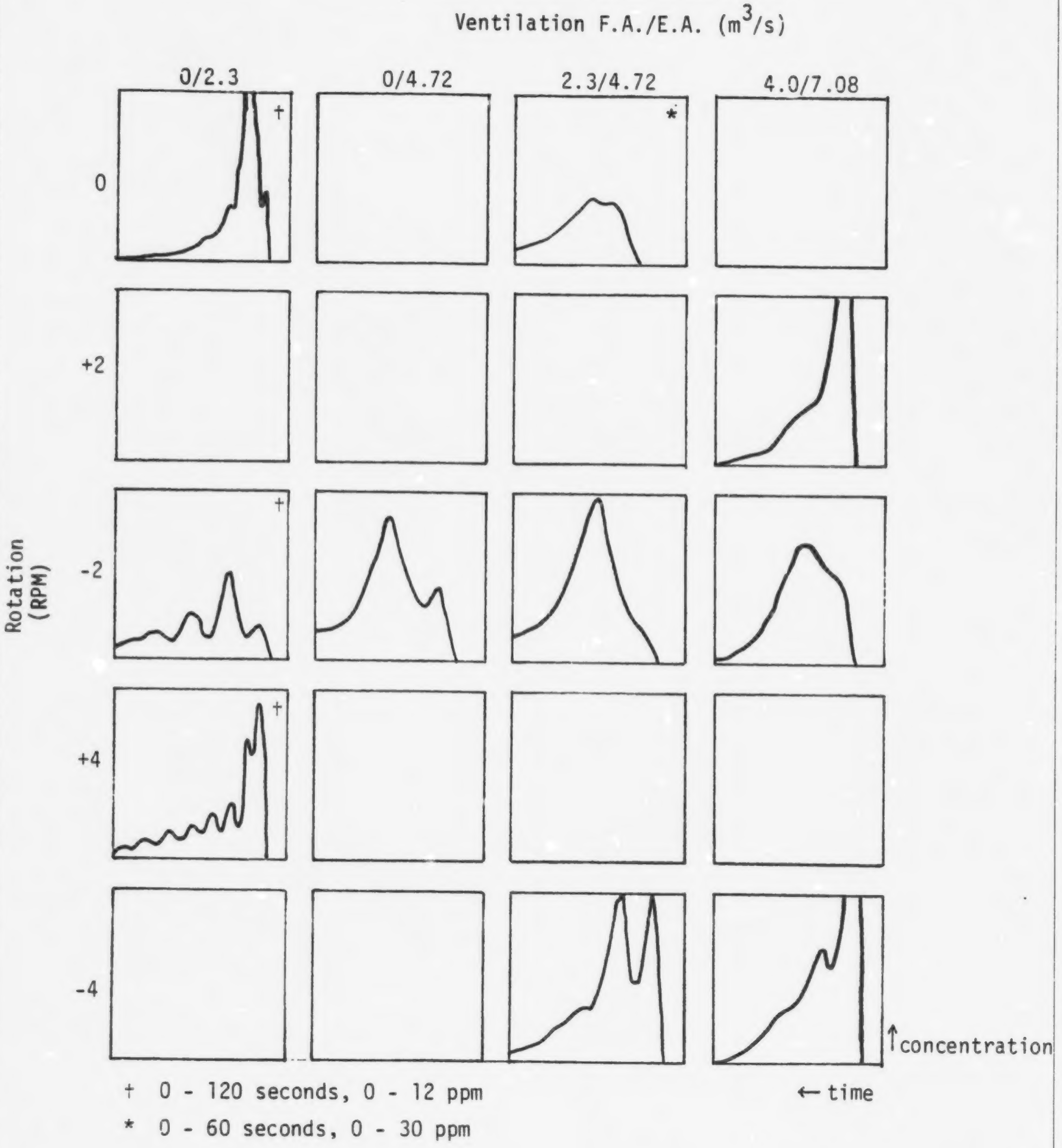


† 0 - 120 seconds, 0 - 12 ppm

ORI

FIGURE 47

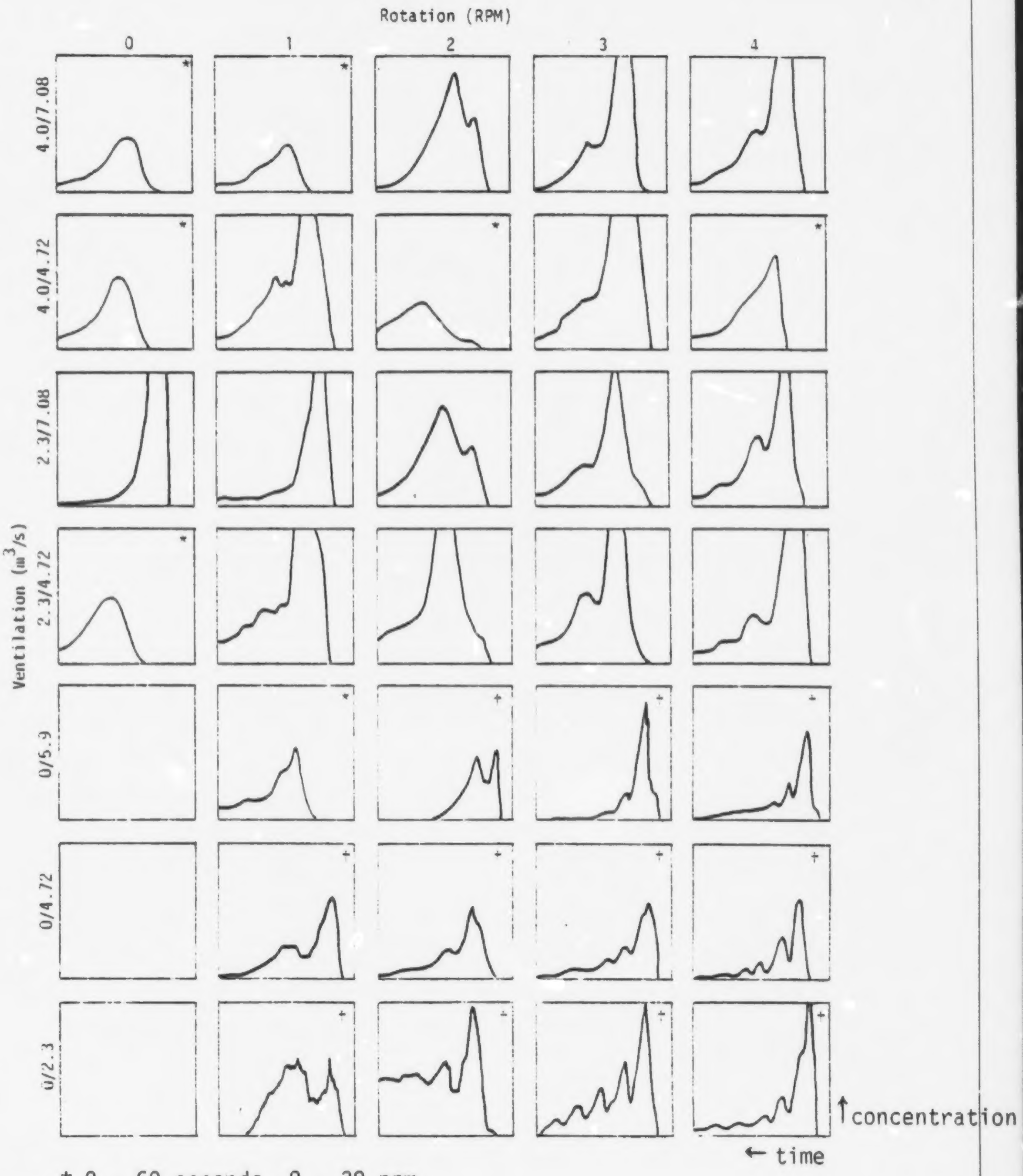
Summary of Traces for Injection Point #22



ORF

FIGURE 48

Traces from Matrix Tests for Injection Point #2

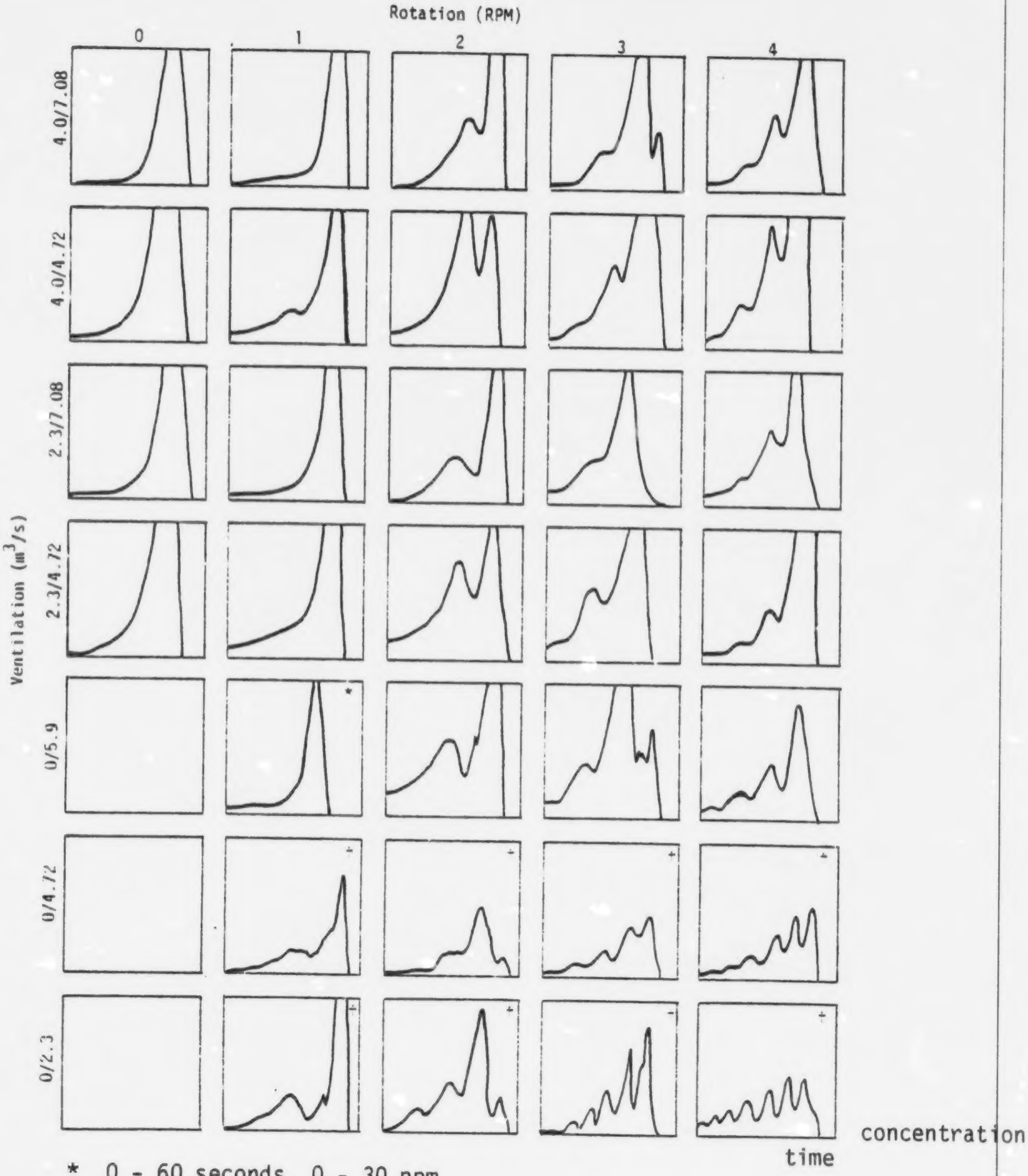


* 0 - 60 seconds, 0 - 30 ppm

+ 0 - 120 seconds, 0 - 12 ppm

FIGURE 49

Traces from Matrix Tests for Injection Point #5

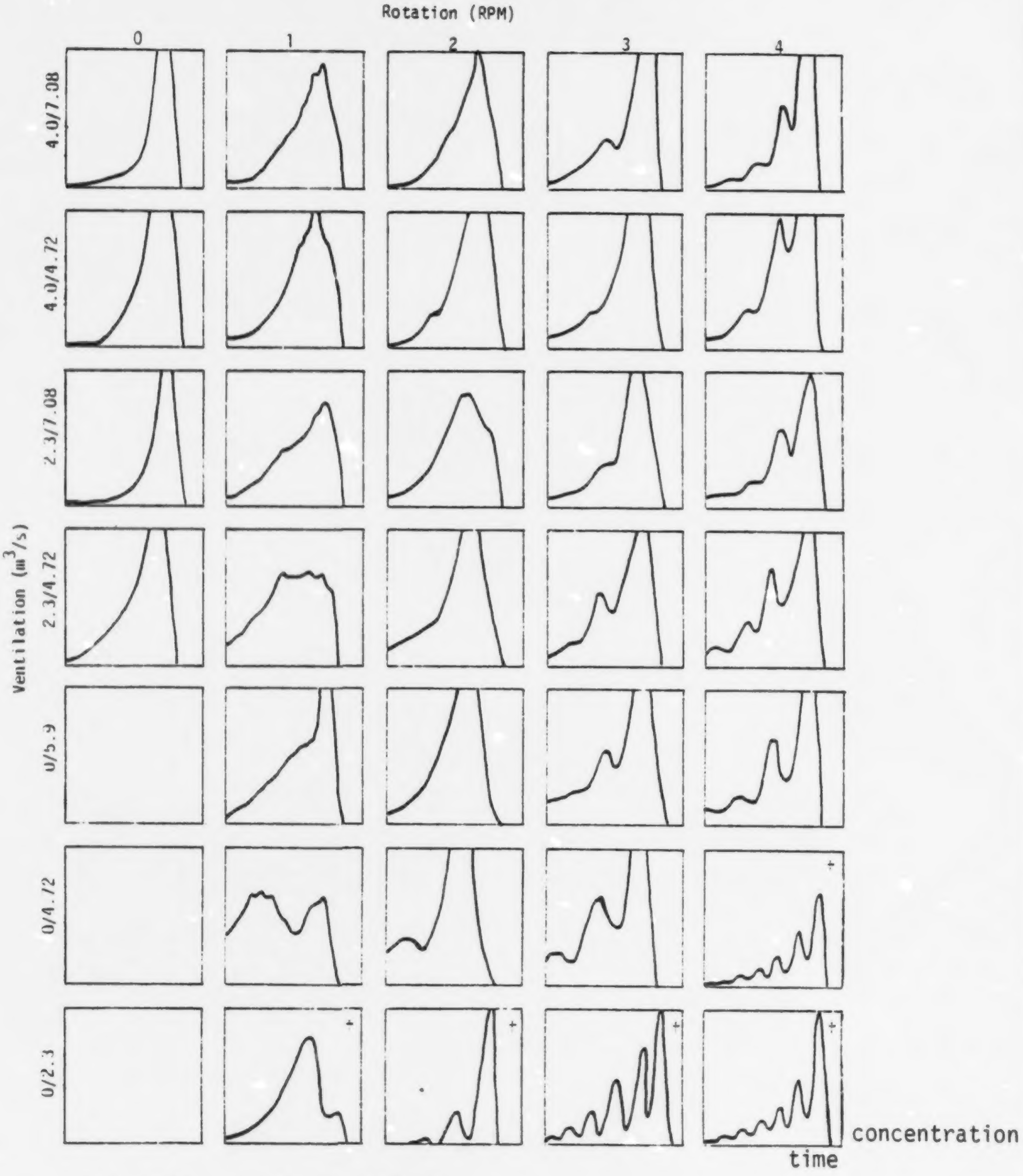


* 0 - 60 seconds, 0 - 30 ppm

† 0 - 120 seconds, 0 - 12 ppm

FIGURE 50

Traces from Matrix Tests for Injection Point #16



† 0 - 120 seconds, 0 - 12 ppm

FIGURE 51

Effect of Tracer Gas Addition Location on Removal Efficiency

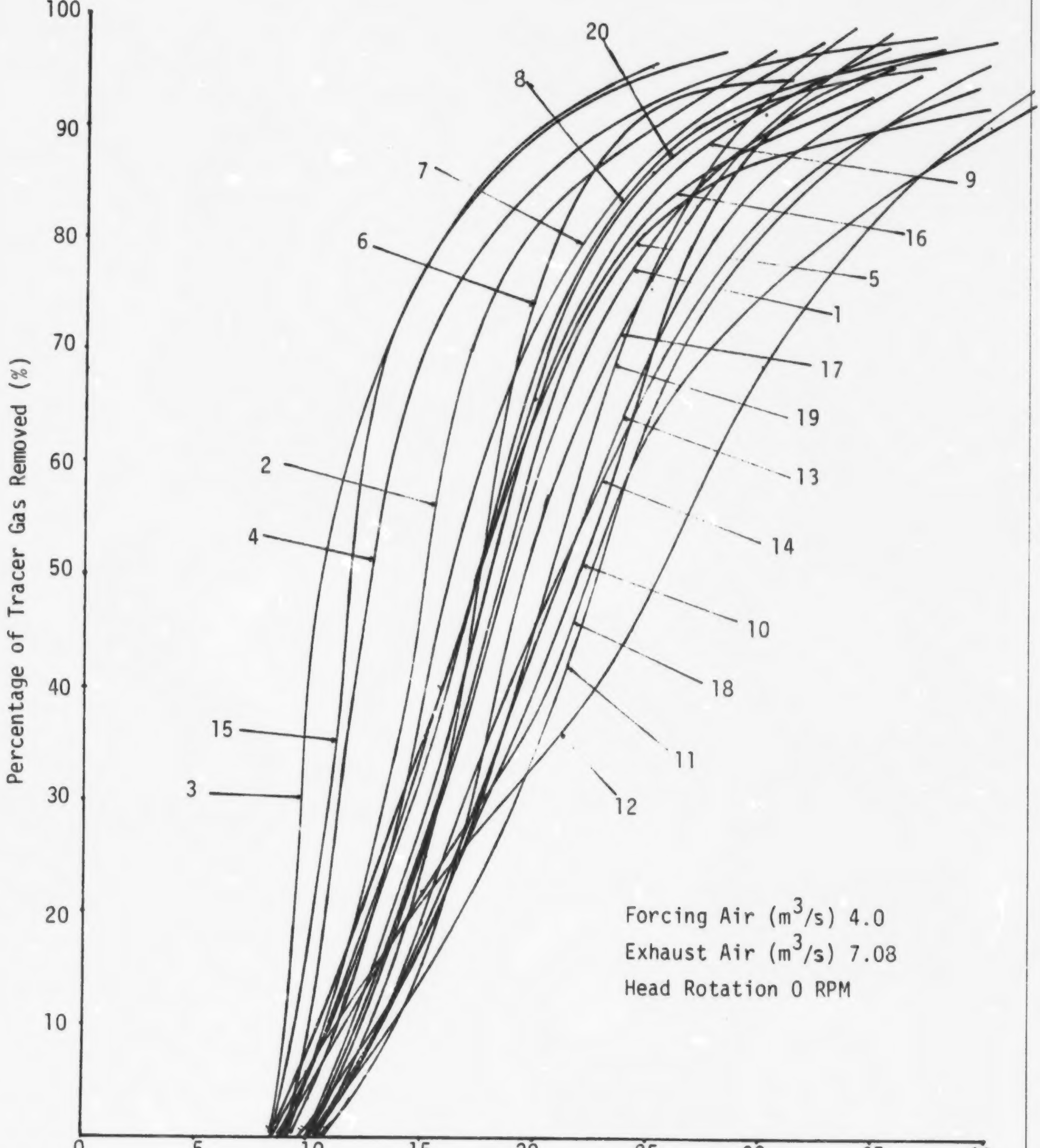


FIGURE 52

Effect of Operating Conditions on Tracer Gas Removal from the Head

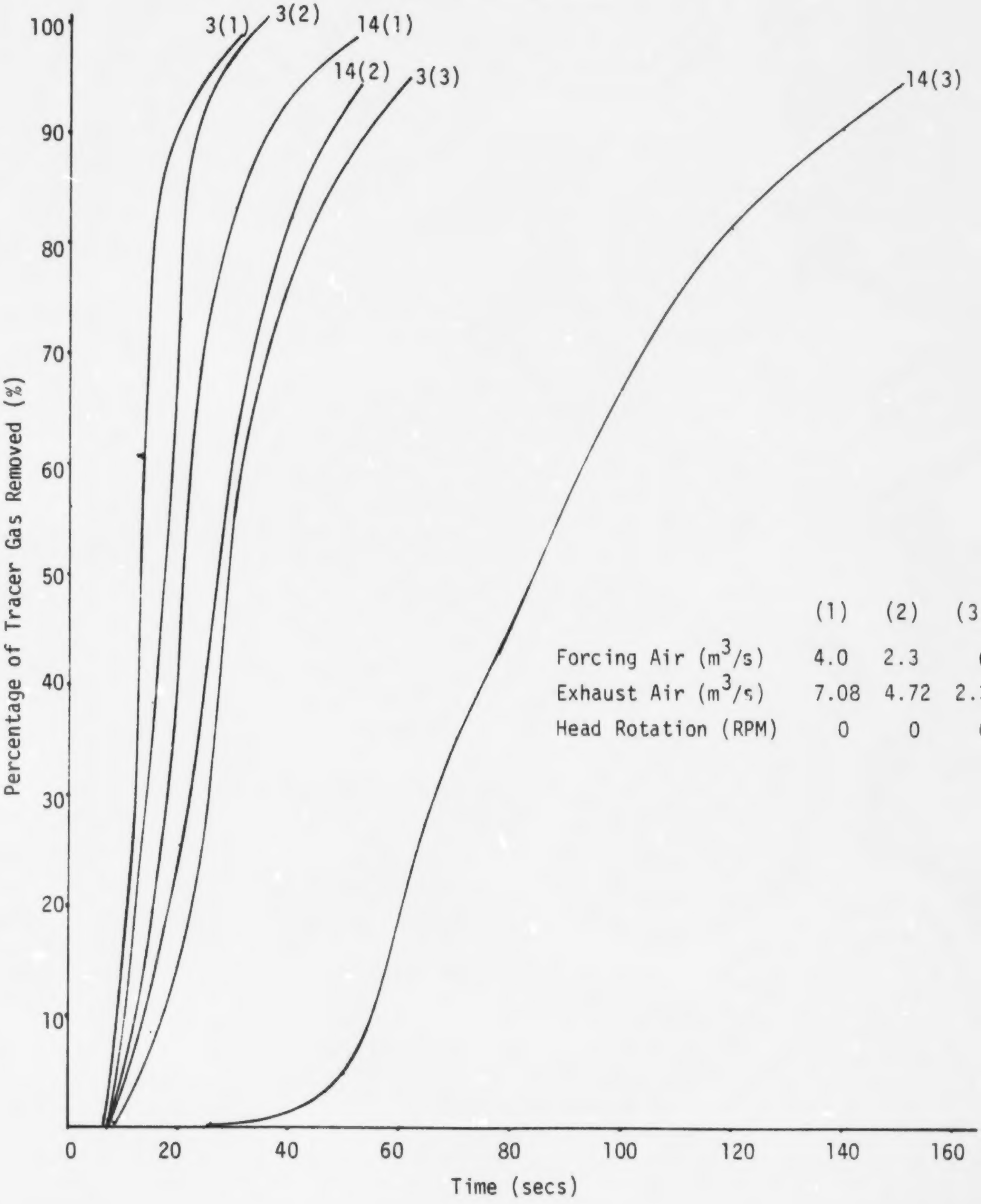
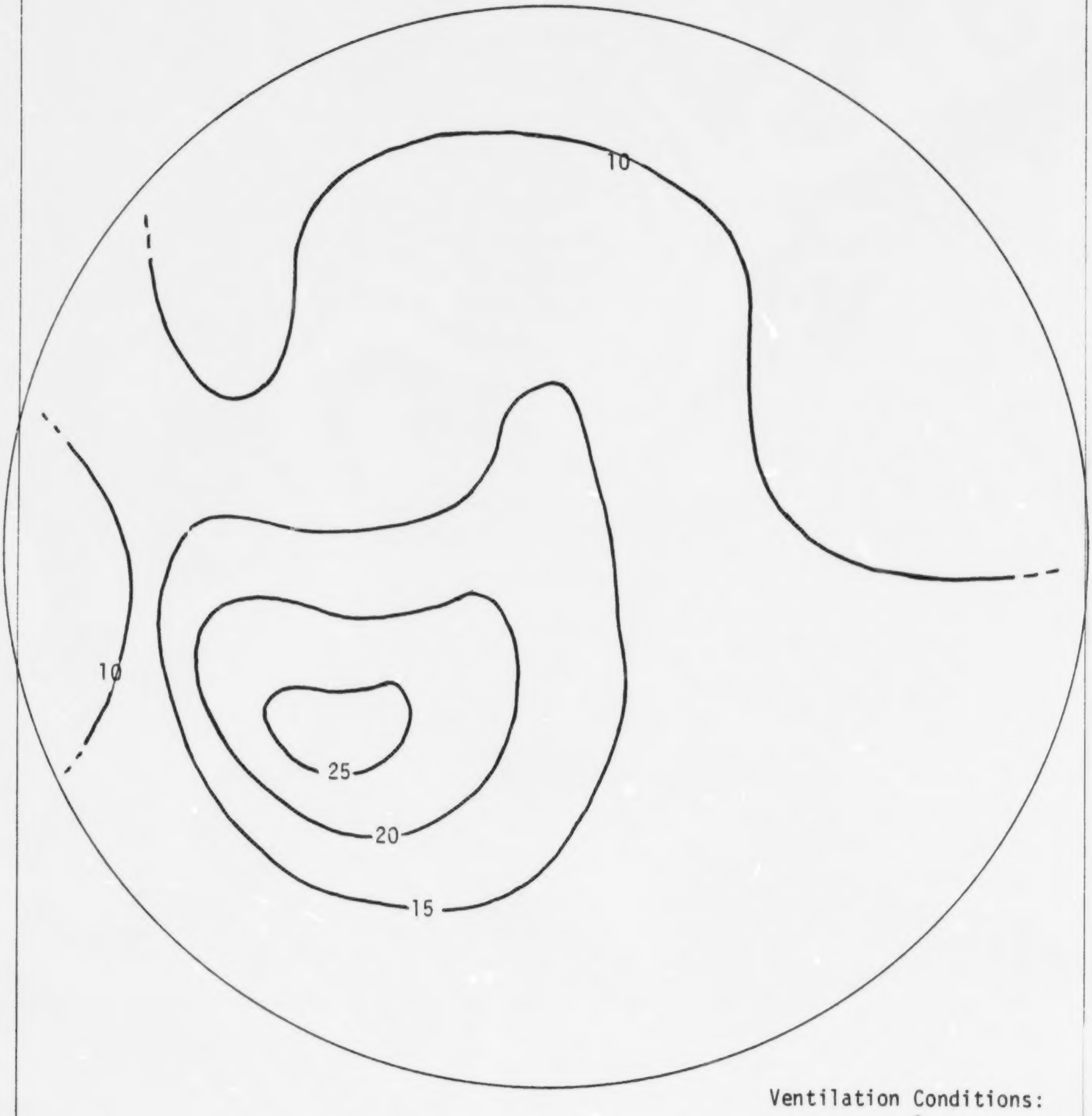


FIGURE 53

Maximum Concentration Isopleths

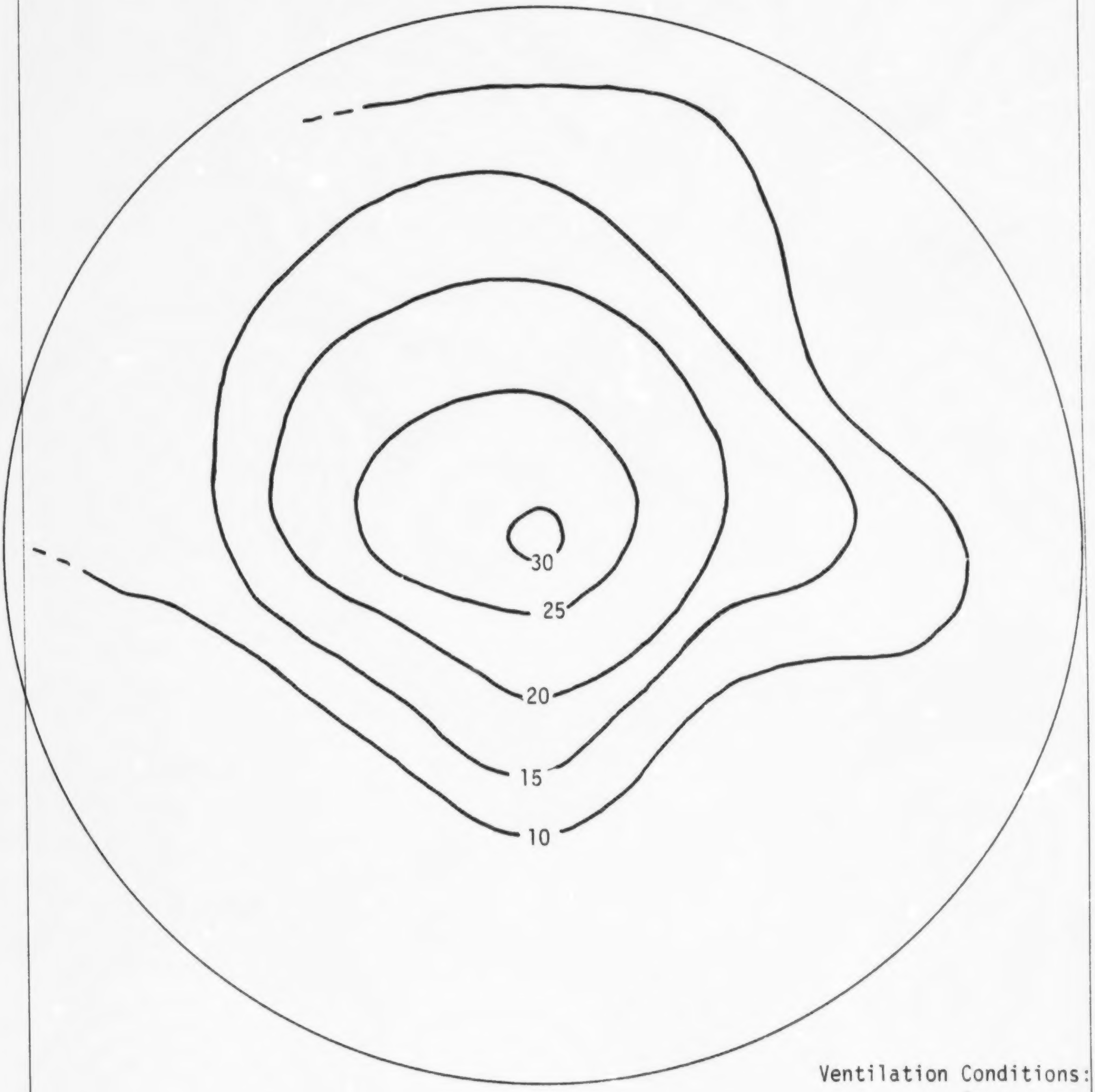


Ventilation Conditions:

F.A. 2.3 m^3/s
E.A. 4.72 m^3/s
Head Rotation 0 RPM

FIGURE 54

Maximum Concentration Isopleths

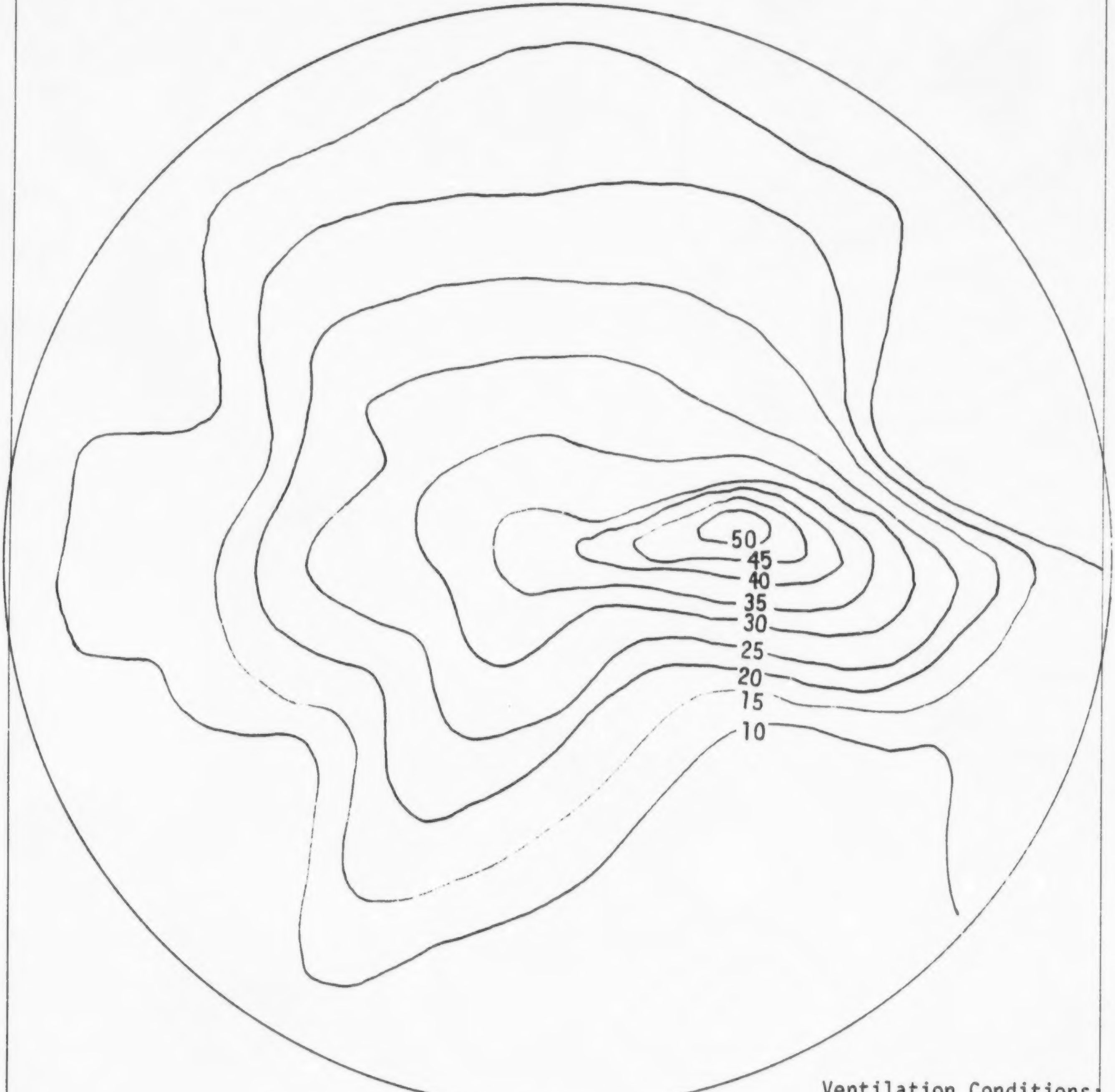


Ventilation Conditions:

F.A. 2.3 m^3/s
E.A. 4.72 m^3/s
Head Rotation 2 RPM cc

FIGURE 55

Maximum Concentration Isopleths

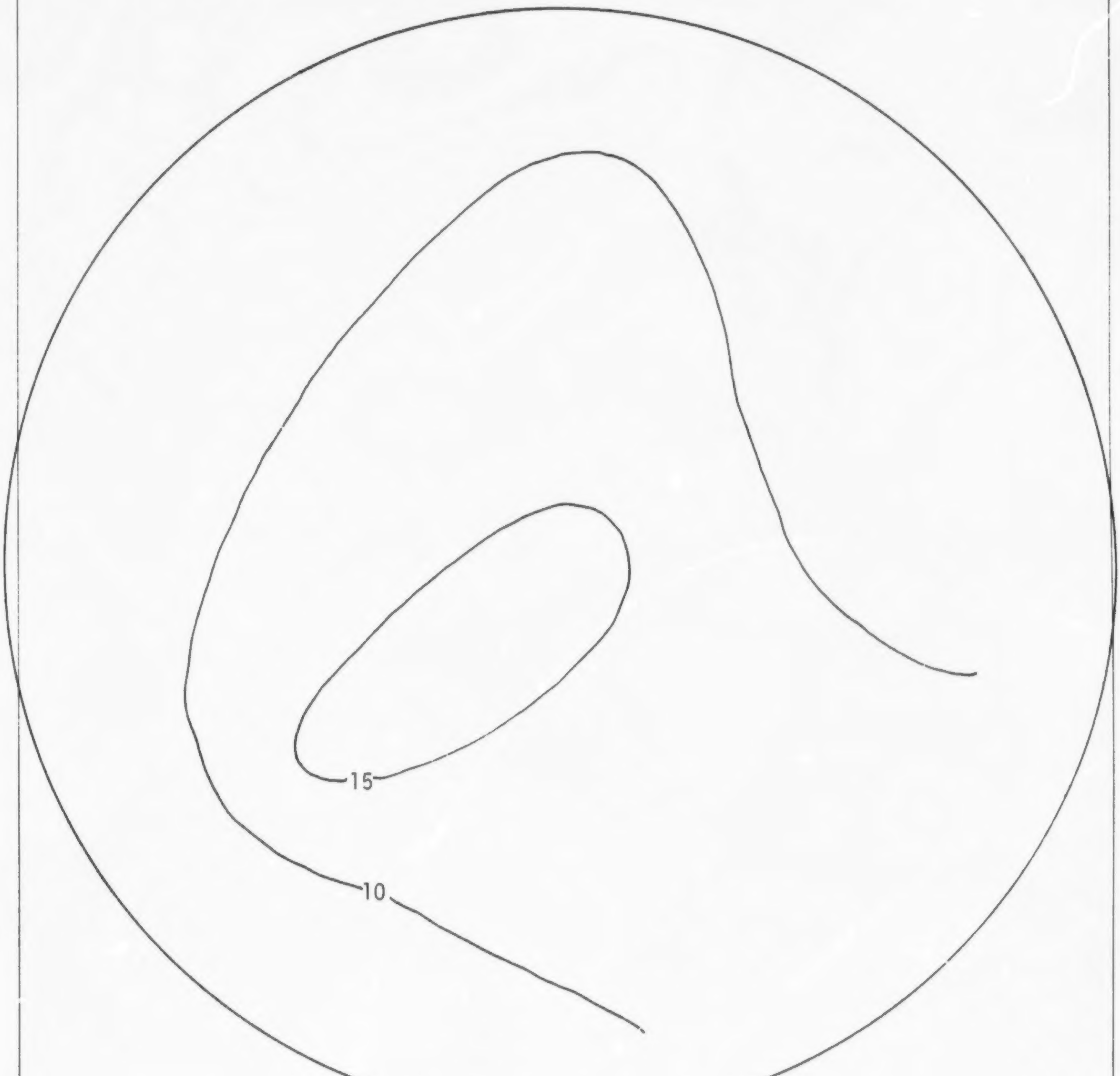


Ventilation Conditions:

F.A. 2.3 m^3/s
E.A. 4.72 m^3/s
Head Rotation 4 RPM cc

FIGURE 56

Maximum Concentration Isopleths

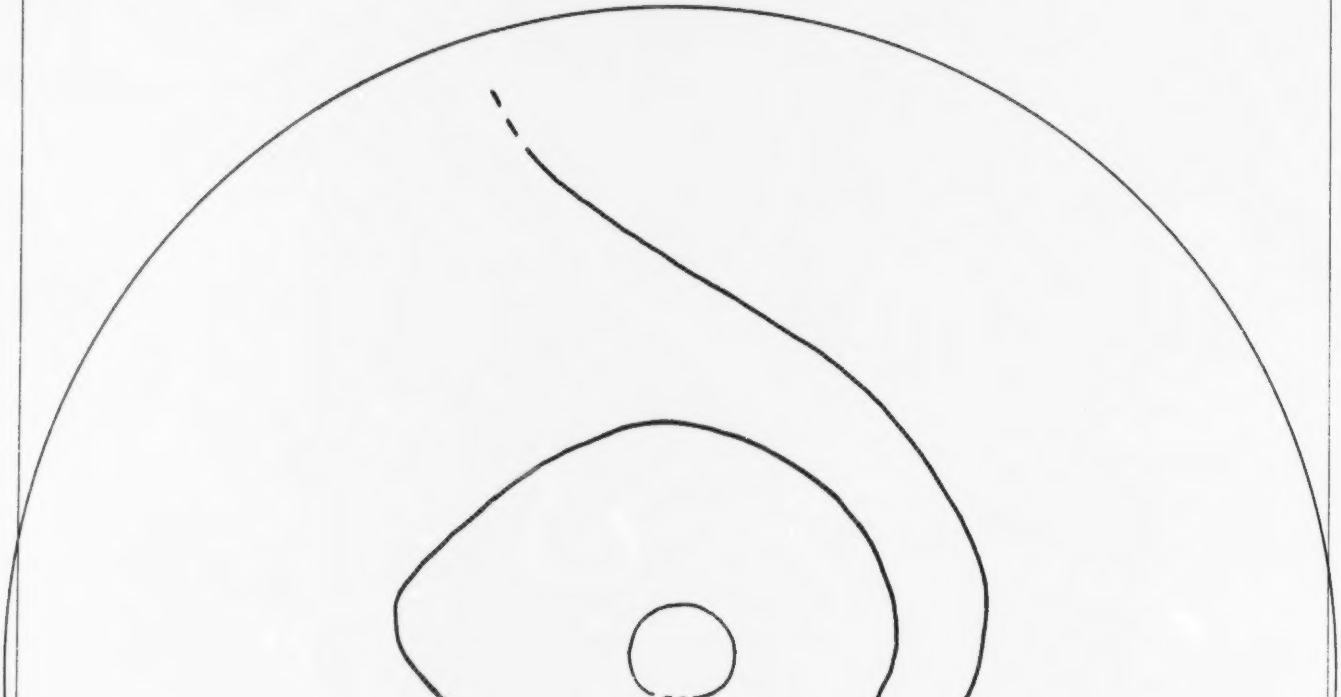


Ventilation Conditions:

F.A. 4.0 m^3/s
E.A. 7.08 m^3/s
Head Rotation 0 RPM

FIGURE 57

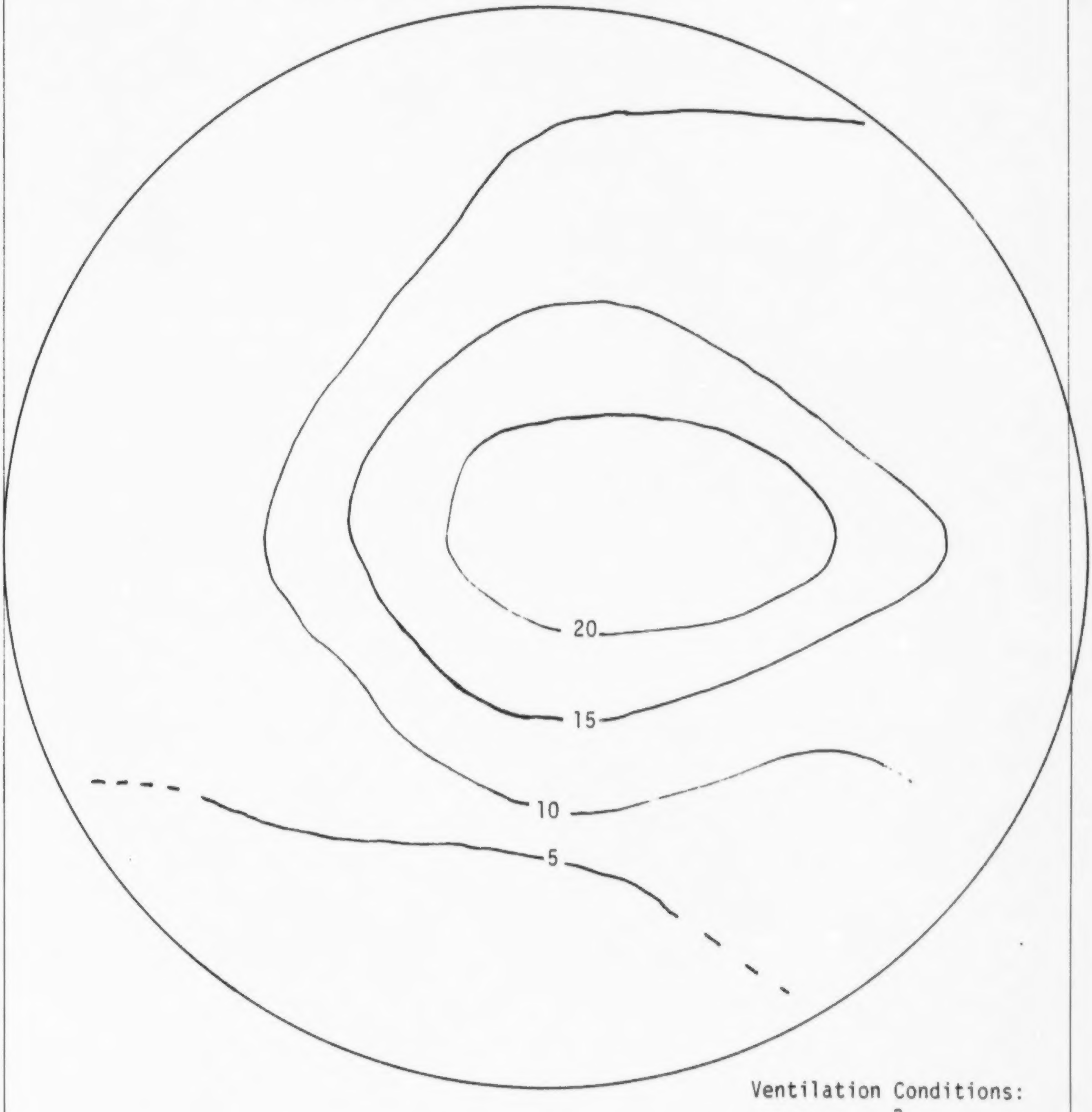
Maximum Concentration Isopleths



Ventilation Conditions:
F.A. 4.0 m^3/s
E.A. 7.08 m^3/s
Head Rotation 2 RPM cc

FIGURE 58

Maximum Concentration Isopleths

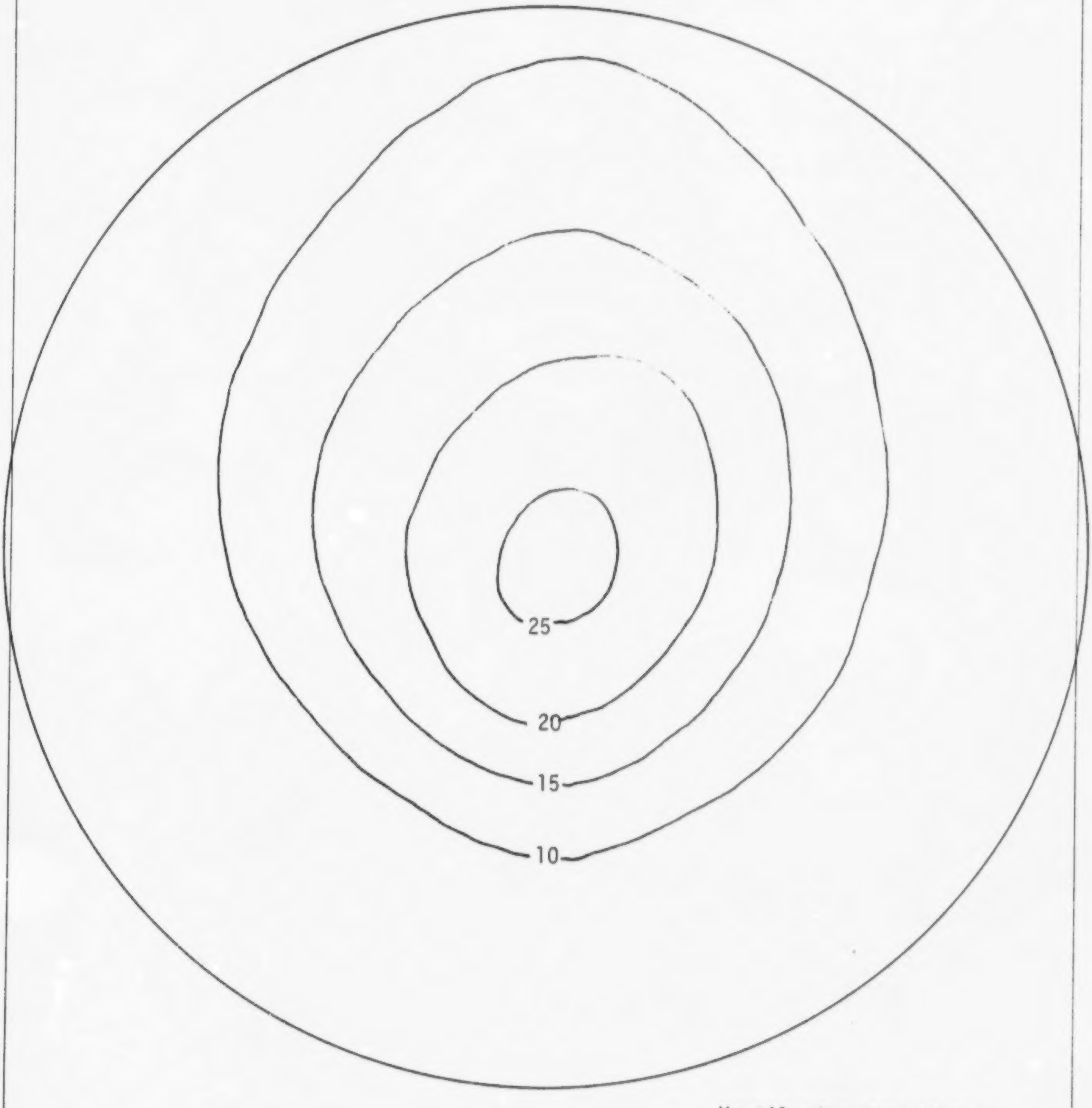


Ventilation Conditions:

F.A. 4.0 m^3/s
E.A. 7.08 m^3/s
Head Rotation 2 RPM c

FIGURE 59

Maximum Concentration Isopleths



Ventilation Conditions:

F.A. 4.0 m^3/s
E.A. 7.08 m^3/s
Head Rotation 4 RPM cc

FIGURE 60

Traces at Injection Point #2 for Specific Ventilation Port Arrangements

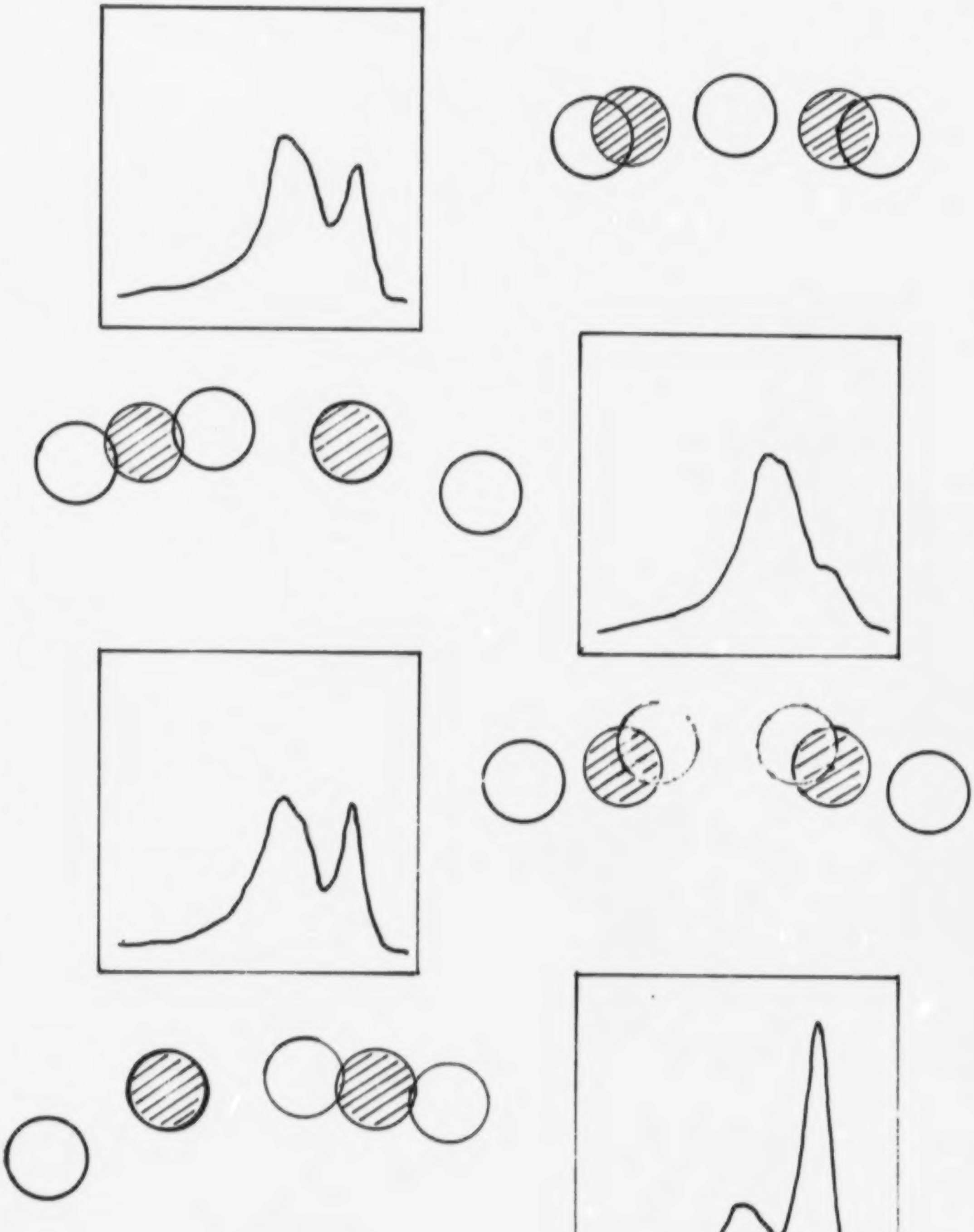


FIGURE 61[3]

Comparison of concentration versus time relationships for four simple models ranging from perfect mixing to complete nonmixing

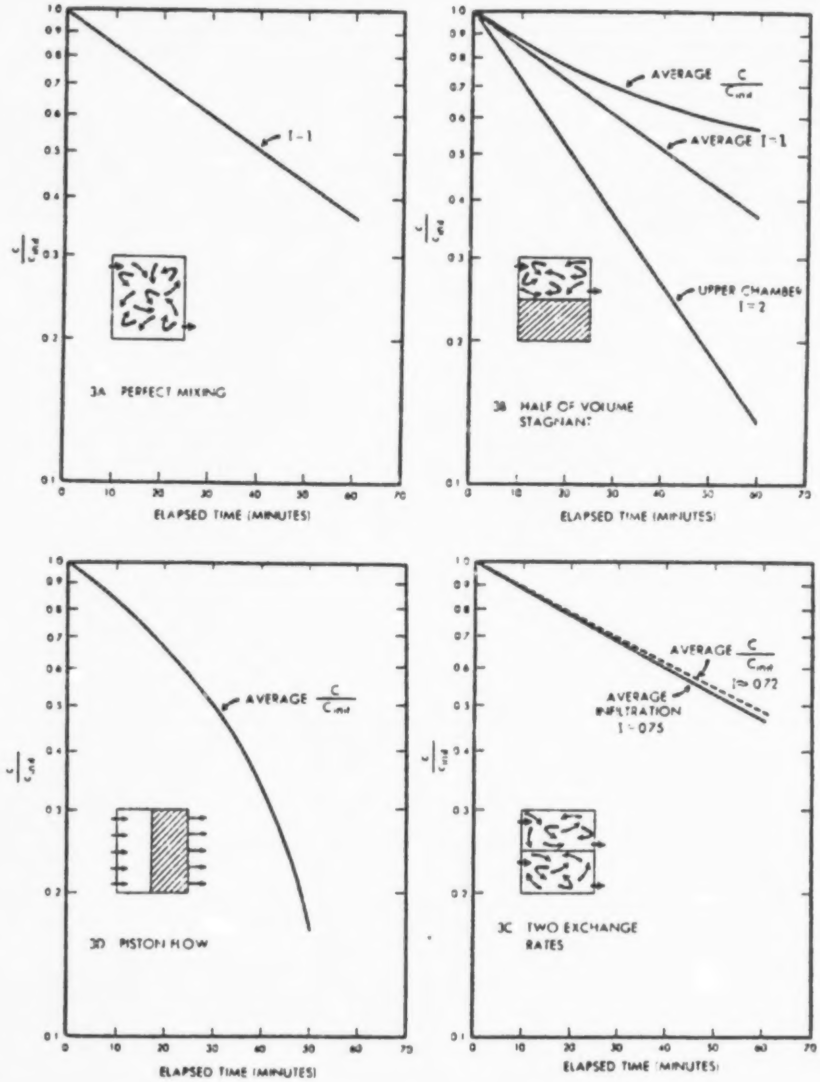


FIGURE 62

Tracer Gas Decay Plots for Addition Points #2 and #11

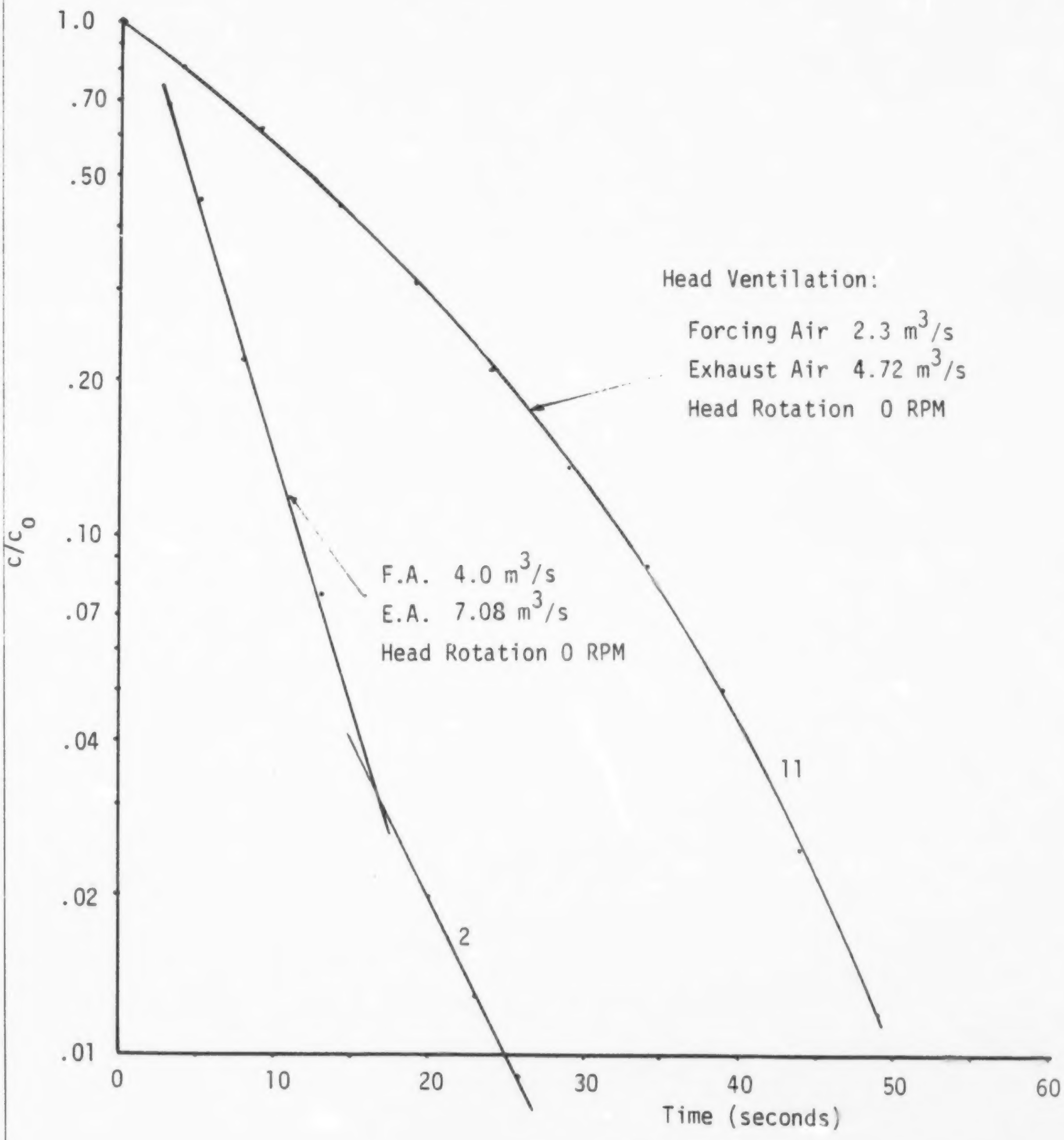


FIGURE 63

Tracer Gas Decay Plots for Addition Point #18

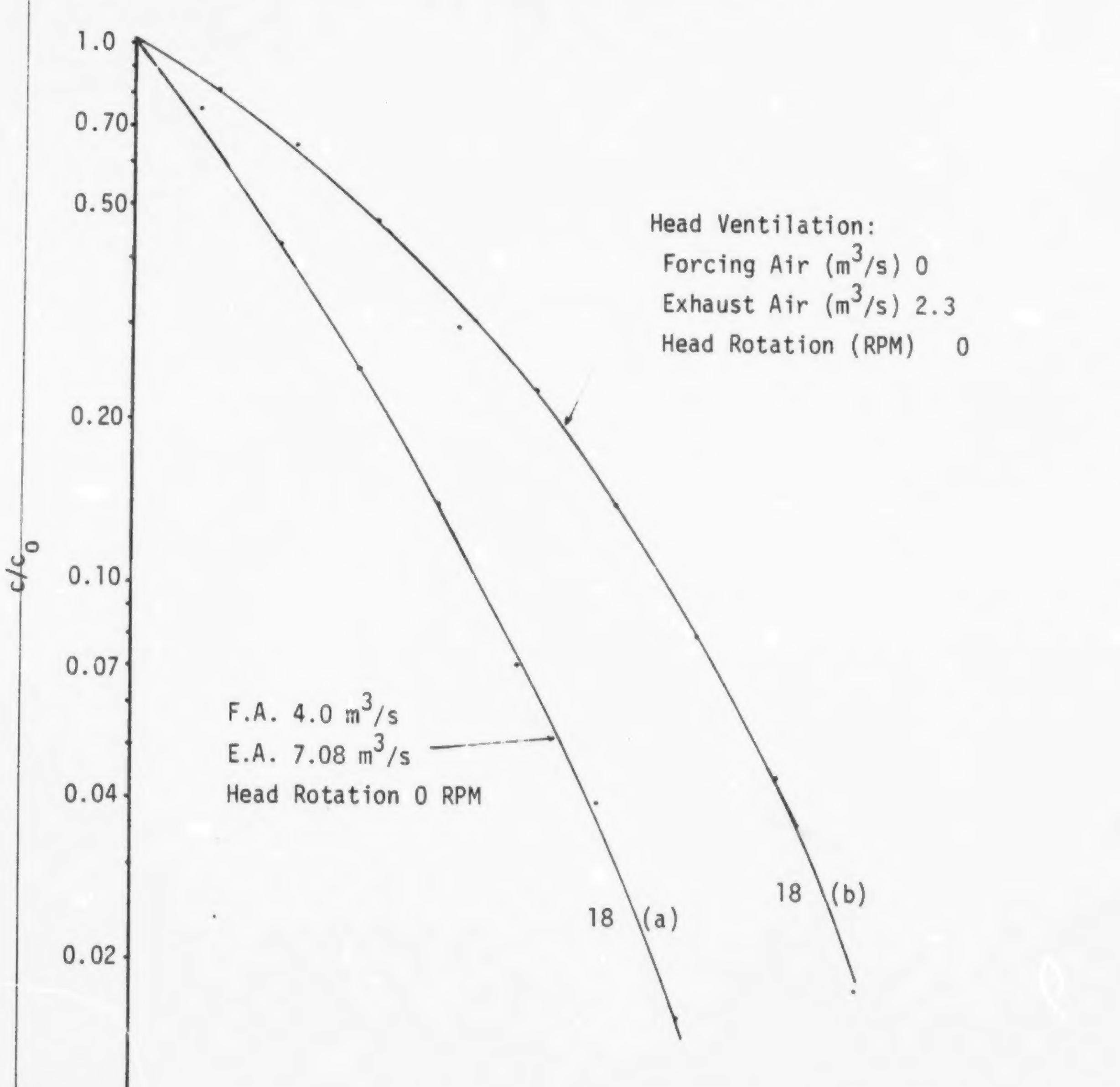
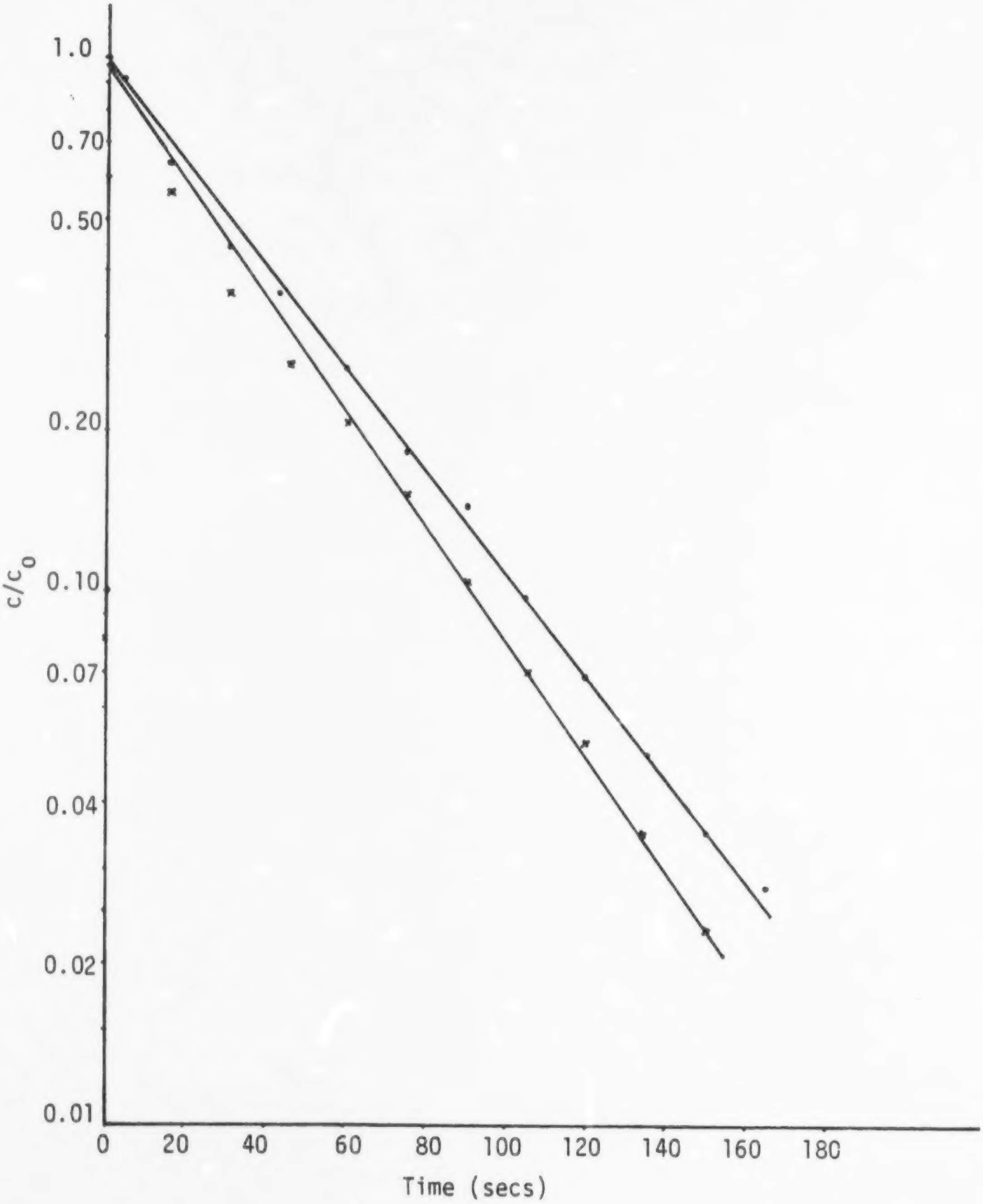


FIGURE 64

Tracer Gas Decay Plots for Addition Points #17 and #19



APPENDIX A

Overlay of Figures 10, 11, 12 and 15

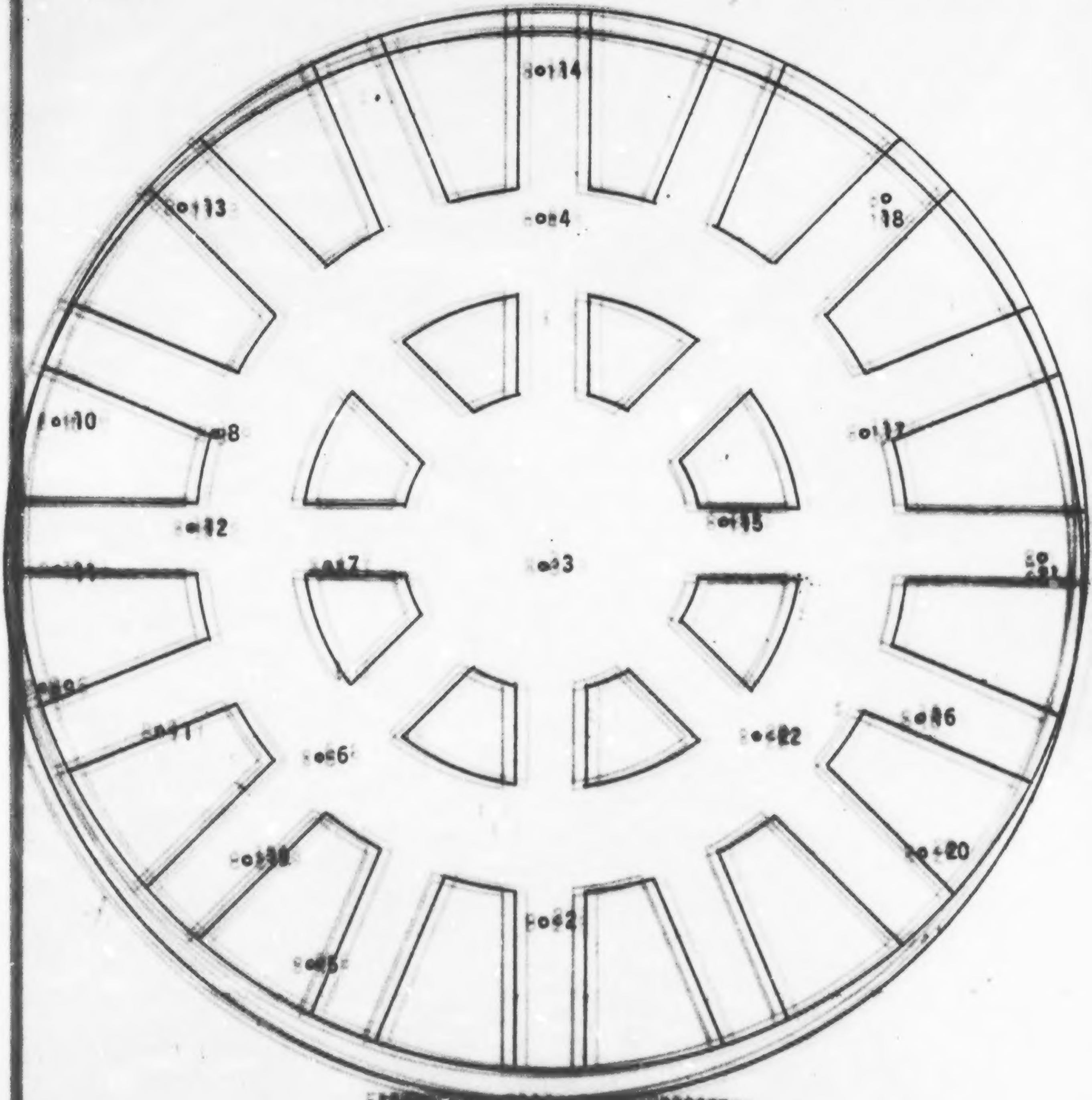

14
13
4
18
10
8
17
12
15
3
7
21
9
11
6
22
16
20
19
2
5

FIGURE [illegible] - [illegible] Pattern

FIGURE 135 - Thermocouple Locations

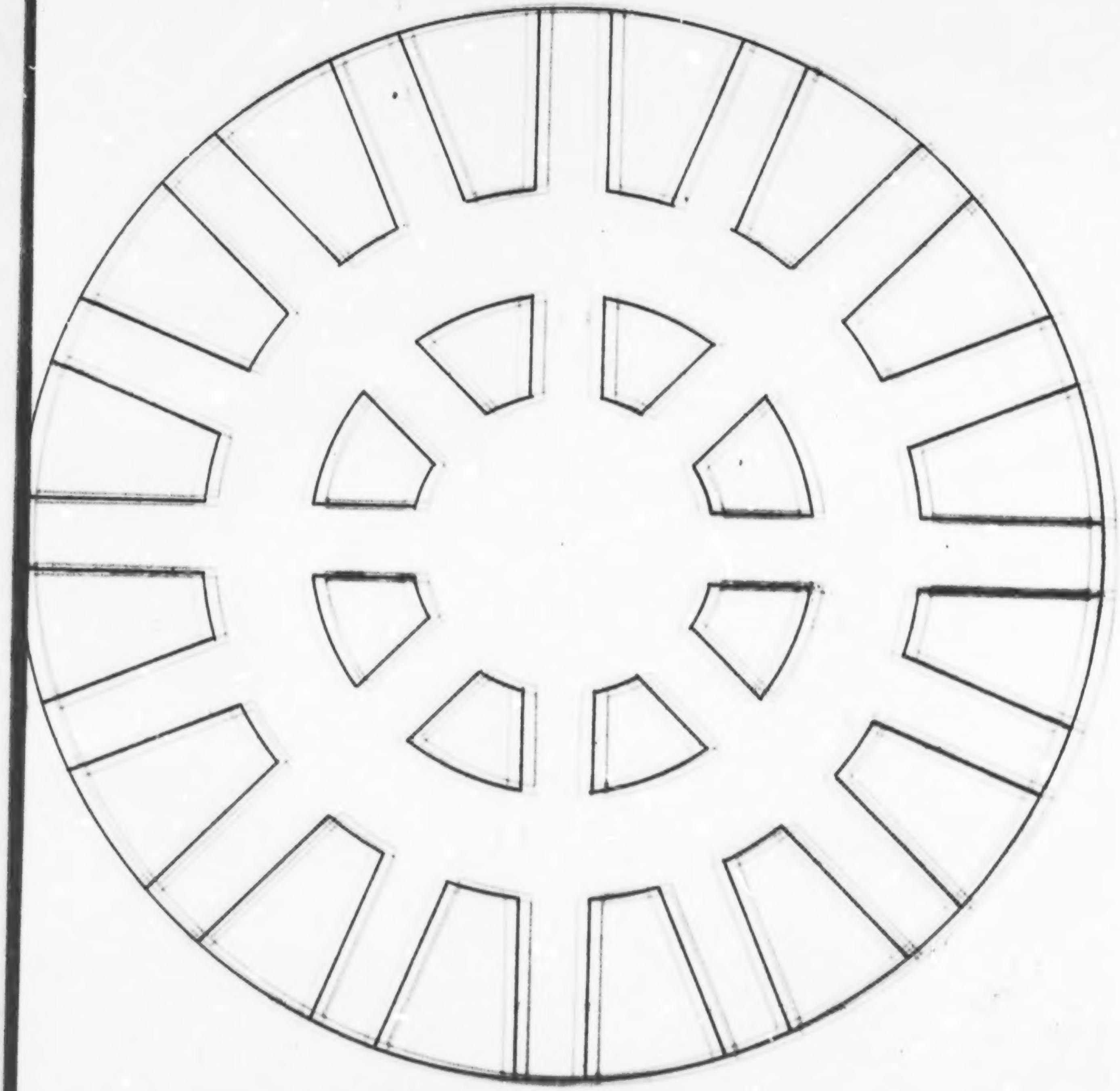


FIGURE 10--Blade Space Pattern

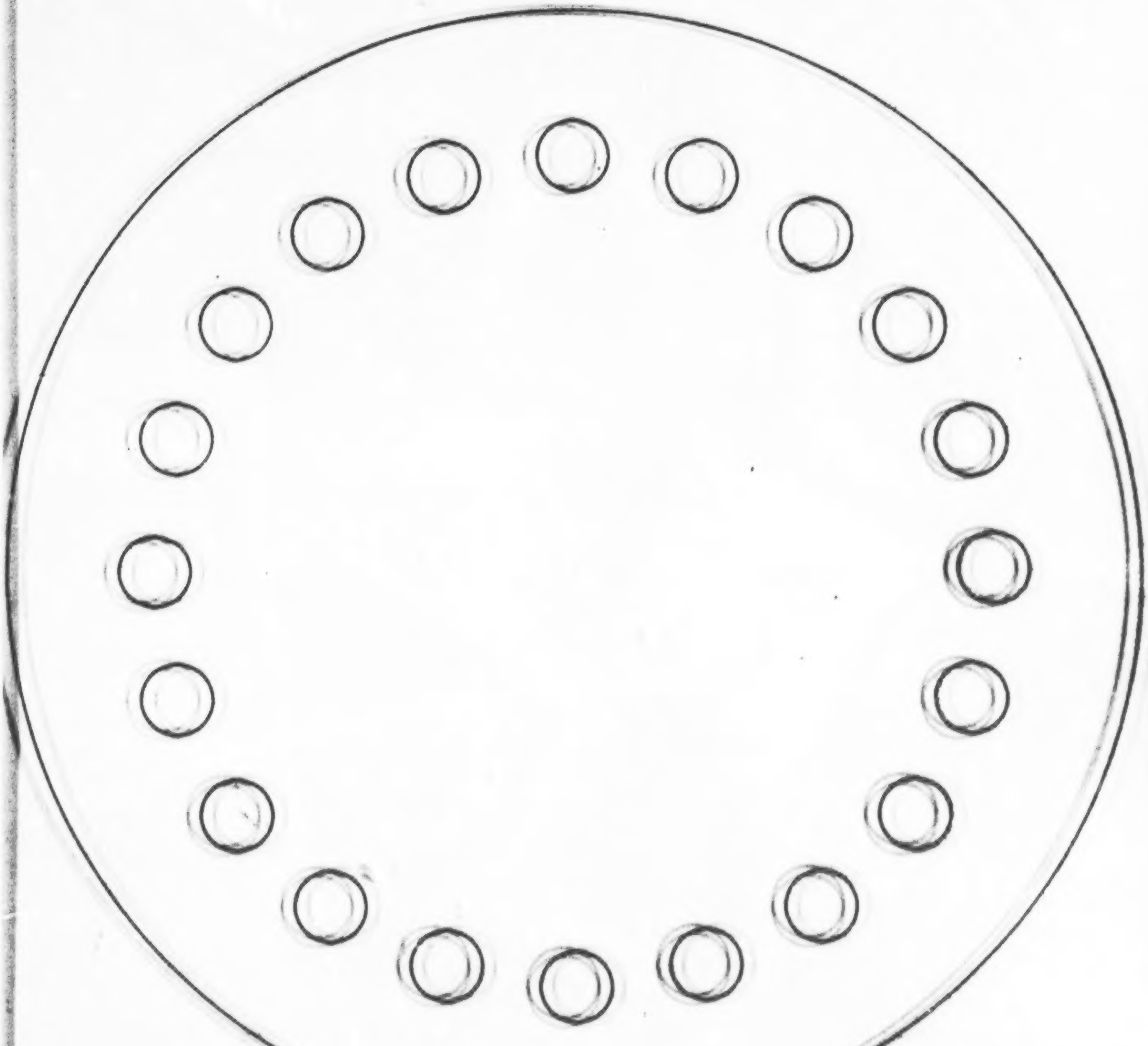


FIGURE 11 - Head Deck Plate Ventilation Holes

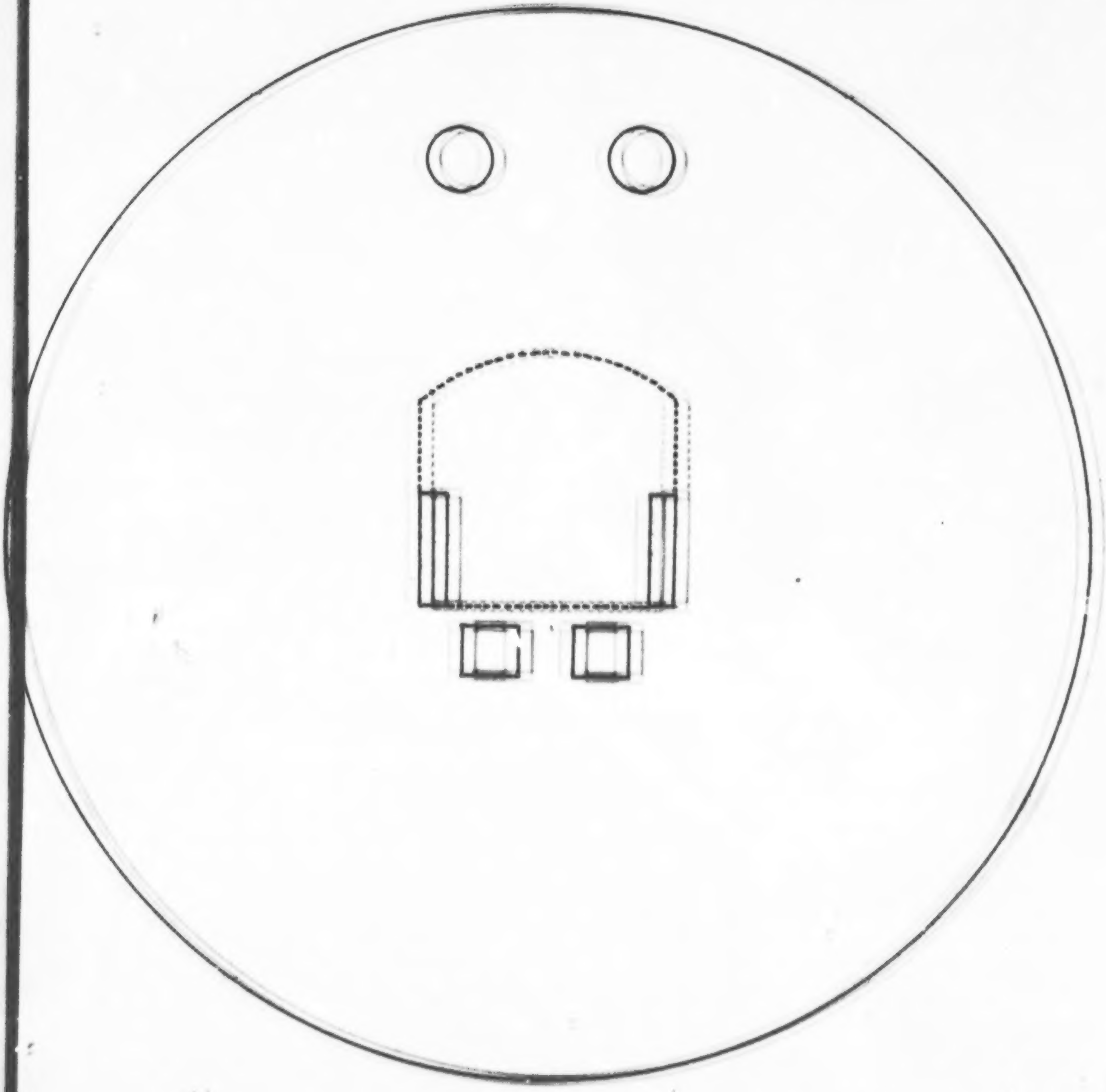


FIGURE 12.--Forcing and Exhaust Airvents.

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